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THESIS

DETERMINATION OF CHANGES IN THE STATE OF THE
ARCTIC ICE PACK USING THE NPS PAN-ARCTIC
COUPLED ICE-OCEAN MODEL

by

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March 2006

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This thesis provides an analysis of the diminishing sea ice trend in the Arctic Ocean by examining the NPS 1/12-degree pan-Arctic coupled ice-ocean model. While many previous studies have analyzed changes in ice extent and concentration, this research focuses on ice thickness as it gives a better indication of ice volume variability. The skill of the model is examined by comparing its output to sea ice thickness data gathered during the last two decades. The first dataset used is the collection of draft measurements conducted by U.S. Navy submarines between 1986 and 1999. The second is electromagnetic (EM) induction ice thickness measurements gathered using a helicopter by the Alfred Wegener Institute in April 2003. Last, model output is compared with data collected by NASA's ICESat program using a laser altimeter mounted on a satellite of the same name.

The NPS model indicates an accelerated thinning trend in Arctic sea ice during the last decade. The validation of model output with submarine, EM and ICESat data supports this result. This lends credence to the postulation that the Arctic not only might, but is likely to be ice-free during the summer in the near future.

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ABSTRACT

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The NPS model indicates an accelerated thinning trend in Arctic sea ice during the last decade. The validation of model output with submarine, EM and ICESat data supports this result. This lends credence to the postulation that the Arctic not only might, but is likely to be ice-free during the summer in the near future.

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I.   INTRODUCTION

A.   IMPORTANCE OF ARCTIC SEA ICE RESEARCH

The importance of research into Arctic sea ice stems from its importance to global climate. Broeker's now classic paper, "The Great Ocean Conveyor," (1991) summarized essentials of global ocean thermohaline circulation. The most critical part of that circulation, North Atlantic Deep Water, comes from the area adjacent to Iceland. In addition to the aforementioned paper by Broeker, there have been a number of others (e.g., Toggweiler, 1994; Dickson et al., 2002; Macdonald et al., 2002; Curry et al., 2003; Curry and Mauritzen, 2005) that conclude that a freshening of the waters in the northern North Atlantic could weaken and perhaps eventually disrupt the pattern of circulation that keeps much of Europe warmer than it otherwise would be. This and other consequences of a slowed conveyor and of Arctic warming in general have been discussed extensively in mass publications from *The Economist* (2005), to *Scientific American* (Sturm et al., 2003), to the *New York Times* (Revkin, 2005).

Three main causes for the freshening of the northern North Atlantic have been proposed. The first is the melting of Arctic sea ice (McPhee et al., 1998). The second is increased precipitation (Curry et al., 2003; Curry and Mauritzen, 2005). The last cause is increased melting of the Greenland ice sheet (Curry at al., 2005; Zwally et al., Science, 2002). Ice thickness and volume is a direct indicator of the former and affects the latter two due to changes in ice-albedo feedback.

In addition to its effect on the world ocean's thermohaline circulation, Arctic sea ice affects world climate due to its albedo, which influences the earth's radiative balance. Since ice and snow have a much higher albedo than open water, there is a positive feedback mechanism set up between solar radiation, the ocean and ice. In this mechanism, more ice means more heat reflected back into space, which leads to colder temperatures, a state that favors more ice. Conversely, more open water has the opposite effect, leading to higher temperatures and less ice. This mechanism, known as ice-albedo feedback and described in detail by Curry et al. (1995), is the cause of polar amplification. According to the theory of polar amplification, outlined by Holland and Bitz (2003), changes in climate, such as global warming, are amplified in high latitudes due to ice-albedo feedback. Again, the study of ice thickness increases our understanding of these mechanisms.

B.   NAVY RELEVANCE

The study of ice thickness in the Arctic Ocean is of critical importance to the United States and the Navy. Up until the present, year-round ice in the Arctic has prevented surface ships from sailing into much of this region. As a result, our national defense preparations for the region have focused on the detection and/or interception of aircraft and ballistic missiles. A reduction in Arctic sea ice to the point where there was no ice at all for part of the year would enable ships to use the region as a short-cut between the northern Atlantic and Pacific Oceans, creating the Northwest Passage dreamed of during the Age of Discovery. Such a reduction would also

increase the use of the "Northern Sea Route" along the Siberian shelf, bringing additional Russian commercial and military shipping into the region.

A Northwest Passage would open up a whole new area of operations for the Navy's surface force. The Navy's surface force would have to be prepared to operate in the Arctic once it is open to foreign surface combatants. Regular commercial shipping through the Arctic would create a requirement for patrols by the Navy and Coast Guard for safety, search and rescue, law enforcement, environmental protection and homeland security. An ice-free Arctic would also necessitate closer naval ties with Canada for combined patrols and surveillance of the area, perhaps along the lines of the North American Aerospace Command (NORAD). At the very least, the American and Canadian governments need to resolve the current dispute concerning sovereignty over Arctic waters (Struck, 2006), a dispute that would be moot if not for the thaw occurring in the Arctic.

The long-term planning implications that the Northwest Passage would create are considerable. The new operating area would require the Navy and Coast Guard to acquire new ships to patrol it, more replenishment vessels to sustain them, and a new logistics infrastructure north of the Arctic Circle. Even with an ice-free passage in summer, the Arctic would continue to be a harsh environment, especially in winter when sea ice would continue to cover most of its surface. We will need to design surface ships and equipment capable of operating in the Arctic on a regular basis. For a more in-depth assessment of the strategic and tactical implications of a warmer Arctic with less ice, readers are referred to the United States Arctic

Research Commission's Special Publication 02-1 (Brass, 2002). Sturm et al. (2003) provides a more general view of current and future changes to the Arctic region wrought by global warming, many of which have profound military implications.

Given the amount of time it takes to specify, design and build military hardware, the Navy will need to decide soon whether or not to acquire Arctic-capable ships and systems. The only way the Navy can determine whether or not to invest in this equipment is to have the best possible estimates of how much more Arctic sea ice will disappear and how quickly it will happen.

C.   CURRENT STATE OF ARCTIC SEA ICE THICKNESS RESEARCH

The Arctic's remote location and harsh environment have led to a scarcity of data in this region. While ice cores were and continue to be the most precise way to measure ice thickness, they are very limited in number and spatial coverage due to level of effort required to obtain them. It was not until the advent of atomic power enabled submarines to travel across the Arctic Ocean submerged, a feat first accomplished by USS NAUTILUS (SSN 571) in 1958, that it was possible to obtain large numbers of ice thickness data (extrapolated from ice draft measurements) over a large area. Most of the ice thickness studies in the 1980s and 1990s used declassified data gathered by submarines.

Bourke and Garrett (1987) estimated Arctic sea ice mean thickness to be 3.3m in summer and 2.8m in winter using submarine data and aircraft laser altimetry data gathered from 1960 through 1982. They also plotted ice

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thickness distribution in 1m bins, noting that though there was more ice in winter, much of it was thin, first-year ice, which accounts for the lower mean thickness in winter. Bourke and McLaren (1992) expanded on this work, including data from more cruises and examining ice roughness.

Rothrock et al. (1999) determined that Arctic ice cover was getting thinner. They compared draft data from cruises between 1958 and 1976 with data acquired between 1993 and 1997. They calculated a 1.3m decrease in mean ice thickness, from 3.1m in 1958-1976 to 1.8m in 1993-1997. This conclusion was supported by Wadhams and Davis (2000), who compared data gathered by HMS SOVOREIGN in 1976 and HMS TRAFALGAR in 1996. They calculated a similar decline in mean ice draft: from 3.1m in 1976 to 1.8m in 1996.

Further research into the thinning ice covert by Tucker et al. (2001), confirmed there had been a dramatic decrease in mean ice thickness at the end of the 1980s. Their study associated the decrease with a shift in the North Atlantic Oscillation (NAO) index (Hurrell, 1995) from the negative regime observed in the mid 1980s to the strongly positive regime seen in the. They concluded that the shift caused a change in circulation that inhibited the accumulation of ice and advected a lot of it out of the Arctic. Studies by Rigor et al. (2002) and Rigor and Wallace (2004) came to similar conclusions by comparing ice conditions with the Arctic Oscillation index, which is highly correlated to the NAO index.

Rothrock et al. (2003) compared results of eight models with ice thickness data obtained by submarines from 1987 through 1997. They found good agreement between the models available to them and observations. Their results

supported the decrease in mean ice thickness mentioned above. They also found that their models showed a slight recovery after 1996. This recovery, however, would prove to be short-lived, as will be seen in Chapter IV.

Holloway and Sou (2002) also combined the study of submarine data and models. Their study disputes the large decrease in sea ice found by others. They believe that though ice became thinner in the area examined by submarines (or at least the area for which data is declassified), it became thicker elsewhere, mostly due to wind-driven advection. They do not, however, dispute the widely-held belief that Arctic sea ice has been decreasing. Rather, they argue that this decrease has been more modest than other studies have maintained due to a bias they feel is imposed by the submarine data release area.

It should be noted that not everyone agrees that Arctic sea ice thickness is decreasing. For example, Winsor (2001) felt that mean ice thickness remained constant during the 1990s. Using data from submarine cruises 1991-1997 (the same data is used in this study), he calculated that there was no trend towards thinning ice cover in the 1990s. This led him to conclude that the thinning that occurred between 1976 and 1996 probably occurred at the beginning of that period. It is interesting to note that the ice thickness distribution numbers shown in the Winsor's paper show a definite decrease in the proportion of thick ice (defined by him as greater than 5m) and a marked increase in thin ice (defined by him as less than 0.3m) in both of his areas of interest, the North Pole and the Beaufort Sea.

Remote sensing has further opened up the study of Arctic sea ice. Studies using passive microwave sensors, such as those of Kwok (2002), Serreze et al. (2003), Comiso and Parkinson (2004), and Stroeve et al. (2005) determined that Arctic sea ice extent/area has been decreasing for some time. Though important, studies that focus on decreasing ice extent/area are probably underestimating the true decline of Arctic sea ice, as will be seen in Chapter IV.

The development of satellite altimetry has more recently enabled sea ice thickness to be measured remotely. While all satellites so far used have suffered from a gap in coverage surrounding the North Pole due to the inclination of their orbits, satellite altimetry offers the advantage of covering the entire Arctic region in relatively short periods of time. This means that it is possible to have near-continuous coverage of the entire region, something that was not possible before the satellite era.

Laxon et al. (2003) used ERS (European Remote Sensing satellite) radar altimeter measurements to determine freeboard, from which an estimate of thickness can be extrapolated (a technique explained in more detail later in this study). They found that ice thickness has a high-frequency interannual variability dominated by changes in the amount of summer melt, rather than changes in circulation. This led them to conclude that, due to increasingly warm summers, the ice pack would continue to thin after the NAO index returned to a negative state. They believed that while a change in Arctic circulation patterns might alter ice thickness distribution, increasing

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melt season length would lead to further overall thinning of Arctic sea ice. In light of the record lows in Arctic sea ice reported in the last few years, this prediction has been proved correct. It should also be noted that Haas (GRL, 2004), using ground-based electromagnetic sounding, obtained independent results that largely agreed with Laxon et al. (2003).

Satellite laser altimetry has the advantage of finer resolution over the radar version. The system (known as the Geoscience Laser Altimeter System, or GLAS) deployed on ICESat (Ice, Cloud, and land Elevation Satellite), also has the advantage of that satellite's higher orbital inclination, making its gap in coverage at the pole smaller than that for previous systems. The system is relatively new and this study uses as yet unpublished data from the ICESat program. The ICESat data is discussed in the next chapter.

II. DATA AND MODEL OUTPUT REVIEW

A.   U.S. NAVY SUBMARINE CRUISE DATA

Upward-looking sonar (ULS) mounted on submarines can measure the amount of ice beneath the surface of the water, its draft. Ice thickness can be extrapolated from its draft by determining the proportion of the total thickness the lies below the surface of the water. For the purposes of this study, a constant factor of 1.12 has been used, as computed by Rothrock, Yu and Maykut (1999).

The data used in this study was obtained from the National Snow and Ice Data Center (NSIDC).   It is all publicly available for download from their website. This data is derived from ULS data taken during 19 cruises between 1986 and 1999. According to the NSIDC,

> Since 1986, data have been recorded digitally with the Digital Ice Profiling System II (DIPS II), with a narrow beam sonar (approximately 3 degrees). All U.S. Navy data in this data set come from the DIPS II system. In processing, data are corrected for depth errors, erroneous drafts are removed, and data are spatially interpolated. The interpolation routine integrates submarine speed and position to obtain drafts at [one meter] spatial intervals. (NSIDC, 2005)

Due to political considerations, only data collected inside the "Gore box" were originally released. The Chief of Naval Operations has since increased the release area somewhat (Figure 1). Most of the data is taken from previously classified sources and so has imprecise dates (only to the nearest third of the month) and positions (nearest tenth of a degree). Data collected during the science-dedicated Scientific Ice Expedition (SCICEX)

cruises conducted in 1993, 1996, 1997, 1998 and 1999 are provided with exact dates and positions to six decimal places. For the purposes of this study, the differences in temporal and spatial precision of the data were considered unimportant as the model output to which it was compared is of far lesser temporal and spatial resolution (model output consists of monthly mean ice thickness in 9km x 9km grid cells).

The accuracy of data collected using this method has been estimated by McLaren et al. (1992) to be ±15cm. Of note, when binned ice thickness distributions (probability functions (PDFs)) for the submarine data sets were plotted, "spikes" were seen at regular intervals in all of them (Figure 2). While it is clear that these spikes are not natural, it is not clear whether they were introduced into the data during the original collection or subsequent data processing. The NSIDC does not know the cause of the problem. Attempts to contact the scientist and the firm contracted to perform the post-cruise data processing have been unsuccessful. For additional information on the submarine ULS data, readers are referred to the NSIDC's website: http://nsidc.org/data/g01360.html (Feb. 2006).
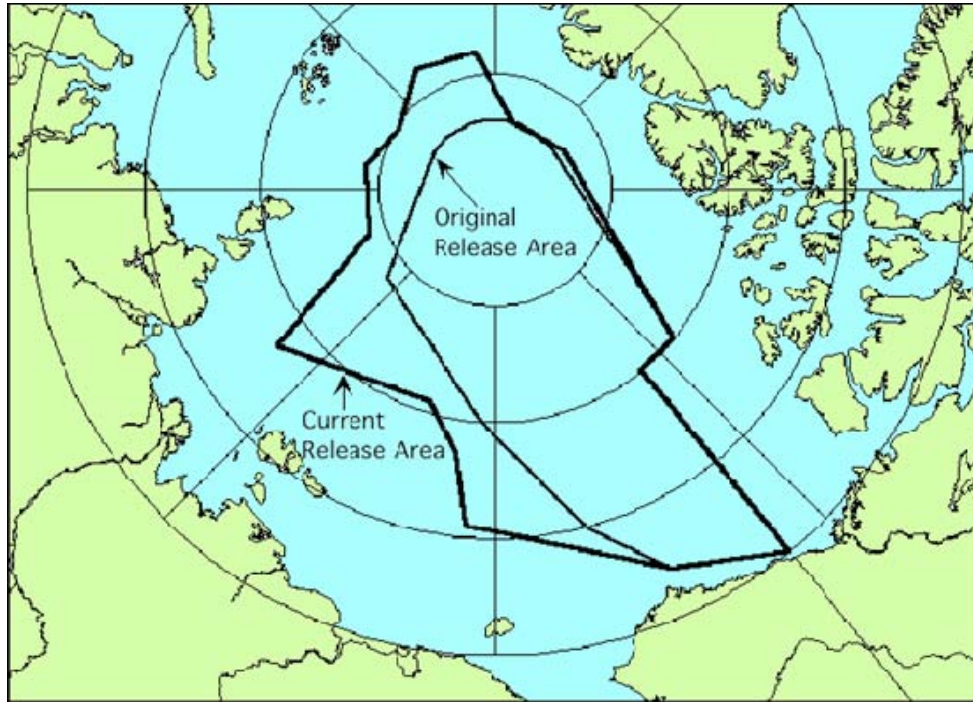
Figure 1.   Original ("Gore Box") and current release areas for
Arctic submarine data [From NSIDC 2005].
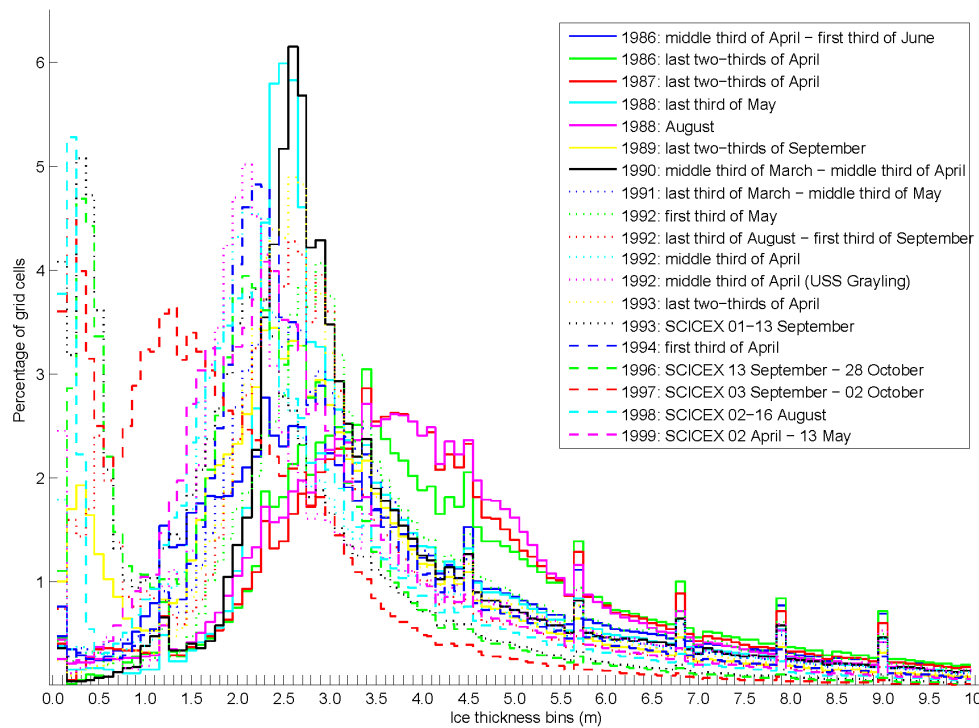
Figure 2.   Ice thickness PDFs for U.S. submarine cruises 1986-
1999.   Note spikes in all data sets at 1.1m thickness
intervals.

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B.   GREENICE 2003 FIELD CAMPAIGN DATA

The EM data used in this study was collected by the Alfred Wegener Institute (AWI) northwest of Spitsbergen using an EM thickness sensor (EM bird) towed by a helicopter embarked on R/V POLARSTERN (Figure 2). The helicopter electromagnetic (HEM) data were collected during eight flights conducted in April 2003. This data and a report on the expedition (Haas, AWI, 2004) are publicly available on AWI's website.

The EM thickness sensor determines detects the distance of the ice/water interface from the EM bird while a laser altimeter measures its height above the surface of the ice. The difference between the two gives ice thickness. The advantage of this system is that it directly measures ice thickness rather than extrapolate it from draft or freeboard. However, the spatial coverage remains a major limitation.

For additional information and a description of the HEM system readers are referred to Haas (AWI, 2004).
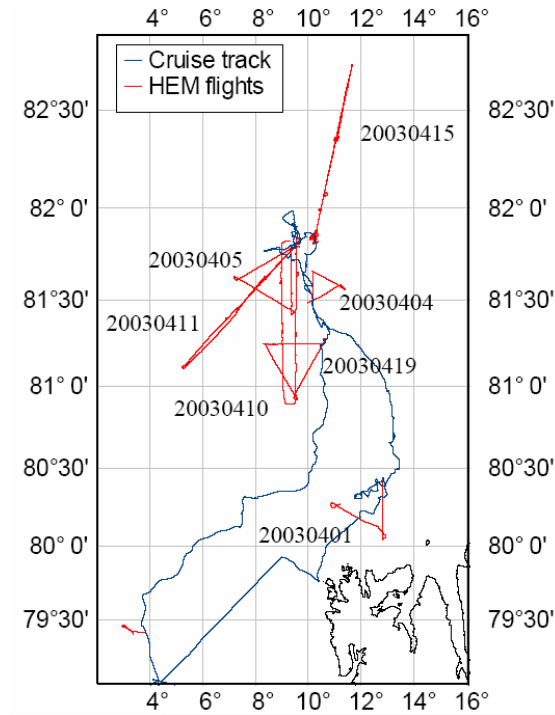
Figure 3.   Cruise track of R/V POLARSTERN during the 2003
        GreenICE field campaign (blue) and ice sections
      surveyed by HEM sounding (red) [From Haas, AWI, 2004].

C.   ICESAT DATA

     ICESat uses a laser altimeter to measure the amount of
ice above the surface of the ocean, its freeboard. Ice
thickness is then computed by determining what proportion
of total ice thickness freeboard makes up and correcting
for snow load. ICESat freeboard measurements and computed
ice thickness data for 20 February through 29 March 2003
and 4 October through 18 November 2003 were kindly provided
by Jay Zwally and Donghui Yi of NASA's Goddard Space
Center.

     The inclination of the satellite's orbit is such that
there is no coverage north of the 86th parallel (Figure 4).
However, the rest of the Arctic region is covered in its

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entirety by data with an along-track spacing of 172m. The
accuracy of ICESat's laser altimeter is 10cm (Zwally et
al., J. of Geodyn., 2002) and its precision is 2-3cm (Yi,
2006). For additional information on the ICESat program
and its data products, readers are referred to the NASA's
ICESat program website: http://icesat.gsfc.nasa.gov.
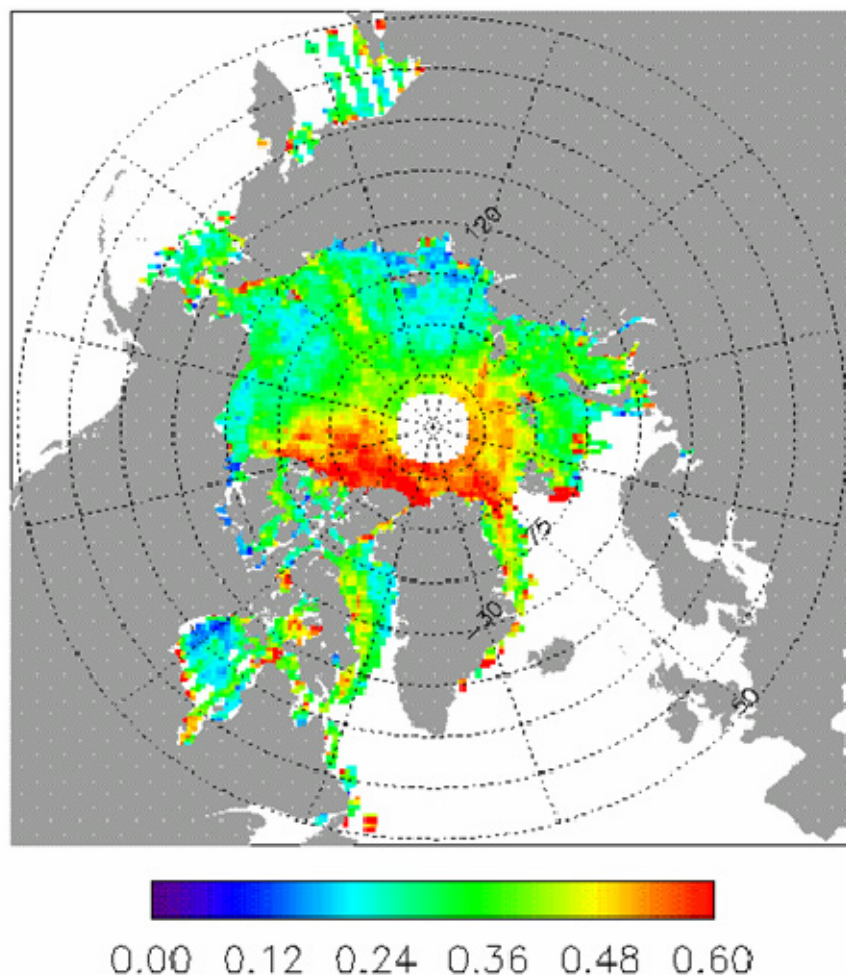
Figure 4.   Map of Arctic sea ice freeboard in 50km grid cells
over the period 20 February through 29 March 2003.
Scale is in meters [Courtesy of Jay Zwally, NASA
Goddard Space Flight Center].

D.   THE NPS MODEL

The NPS model domain (Figure 5) includes all ice-covered waters in the northern hemisphere, including the sub-Arctic North Pacific and North Atlantic Oceans, the Arctic Ocean, the Canadian Arctic Archipelago and the Nordic Seas. The model is configured using a horizontal, rotated spherical grid covering 1280x720 cells at a 1/12 degree (approximately 9km) resolution. It has 45 vertical layers and bathymetry in the Arctic Ocean is derived from the 2.5km resolution International Bathymetric Chart of the Arctic Ocean (Maslowski et al., 2004).
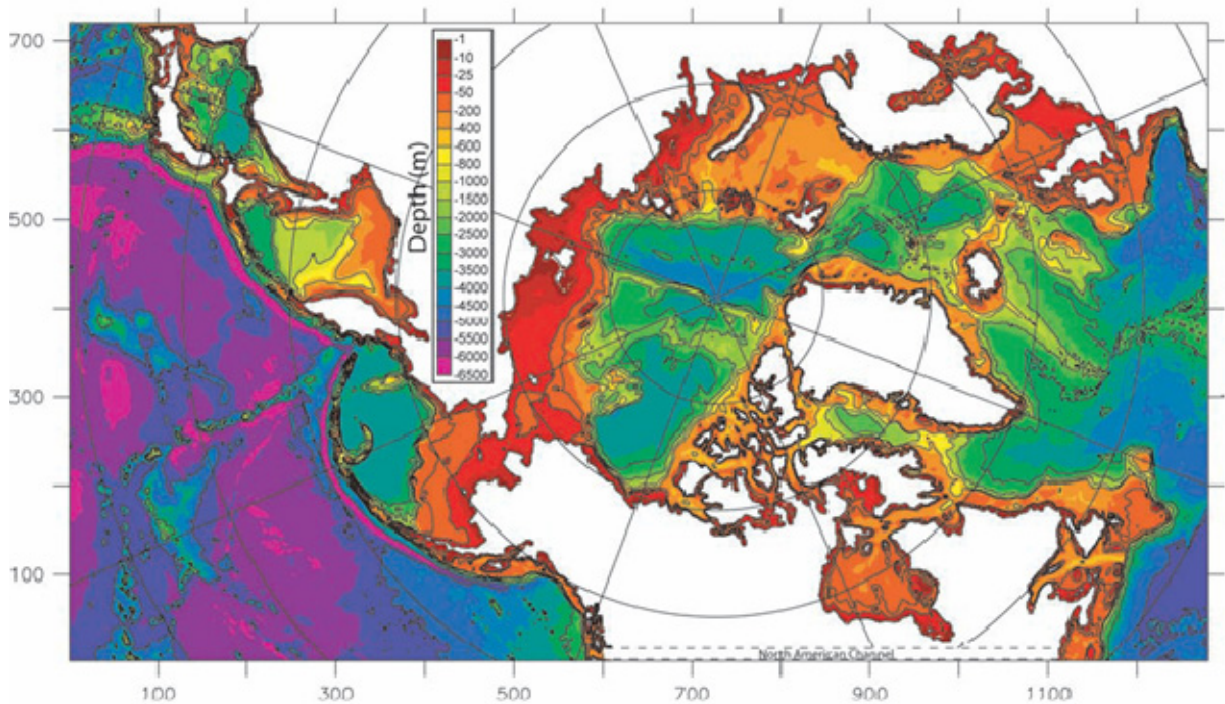
Figure 5.   The NPS model domain and bathymetry. Two dashed lines across Canada indicate the location of an artificial channel connecting the North Atlantic and the North Pacific to balance the net northward water transport through the Bering Strait [From Maslowski et al., 2004].

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It can be seen from Figure 5 that the region of interest, the Arctic Ocean, is far away from the lateral boundaries of the model. Boundary effects are therefore unlikely. The ocean surface level, 5m thick, is restored on a monthly timescale to monthly temperature and salinity climatology from University of Washington Polar Science Center Hydrographic Climatology 1.0. This was a correction term to the explicitly calculated fluxes between the ocean and overlying atmosphere or sea ice (Maslowski et al., 2004).

Atmospheric forcing fields include 10m east-west and north-south wind velocity components, surface pressure, temperature and dew point, and long-wave and short-wave radiation. The forcing data was interpolated into the model grid (Maslowski et al., 2004).

The results of the model run used in this study are datasets that include monthly average ice thickness in each model cell for the years 1979-2003. For additional information on the model readers are referred to Marble (2001), Preller et al. (2002) and Maslowski et al. (2004).

III. RESULTS

A.   COMPARISON OF SUBMARINE CRUISE DATA WITH MODEL OUTPUT

Determining the skill of the model's ice thickness estimates requires a comparison of its output with the submarine ULS-derived ice thickness. This comparison is problematic for several reasons. The main one is that the data and model output are at very different spatial resolutions; the former is 1m along-track, the latter is a cell of about 9km x 9km. Figure 6 shows the ice thickness PDF of the 1999 SCICEX cruise overlaid with the PDF of the model cells crossed by the submarine track. The model output plot is much taller and narrower than that of the cruise data. This is due to the much lower number of points plotted and because the cells only have average values of ice thickness, which tends to remove values at either extreme.

Since part of the problem is the huge mismatch between the number of data points and the number of cells plotted (three orders of magnitude), one could try to increase the number of model cells plotted. This can be accomplished by computing the PDF of a three-cell wide swath of cells: the cells the submarine traveled through and those cells immediately to either side of them. Figure 7 shows the result using the 1999 SCICEX cruise (2 April through 13 May 1999) again as an example. This turns out to be no more enlightening than the original plot.

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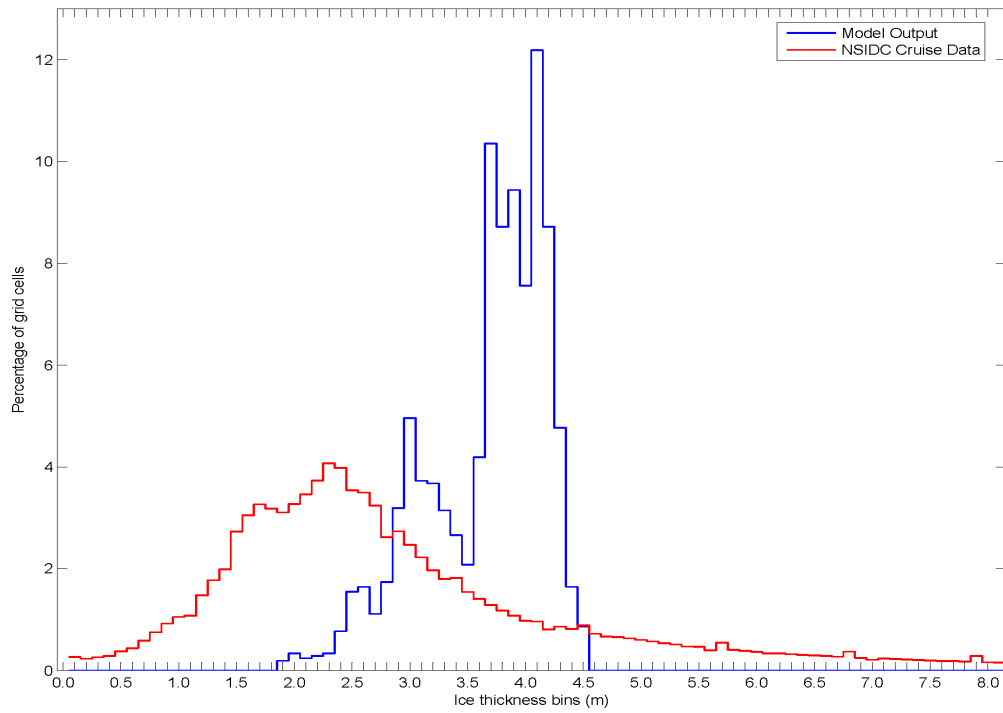
Figure 6.   1999 SCICEX cruise ice thickness PDF and
corresponding PDF of model monthly mean.
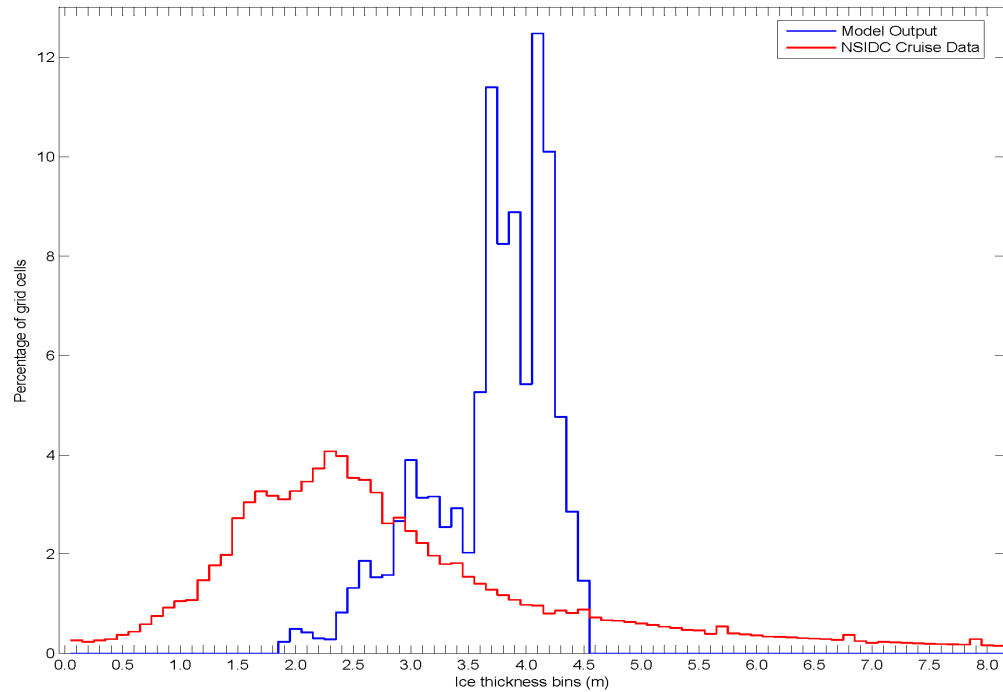
Figure 7.   1999 SCICEX cruise ice thickness PDF and
corresponding PDF of model monthly mean for a three-
cell wide swath.

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Clearly the problem in the above two comparisons is that they compare two very dissimilar datasets, an "apples to oranges" comparison. A more "apples to apples" comparison was conducted by averaging the ice thickness for each segment of the cruise (each segment is straight and corresponds to a distance traveled of 50km or less). The comparison of segment-averaged PDFs and the PDFs of model average thickness corresponding to the same segments yields plots, such as Figure 8, that lend themselves to more direct comparison.

The flaw in the analysis above is that the segments are not all of the same length, but they all have the same "weight." The final step to having a valid comparison between the submarine ULS data and the model output is assigning weights to the segments according to their lengths. For the 1999 SCICEX cruise, this method yields Figure 9.

It can be seen from Figure 9 that the model in fact represents the 1999 SCICEX cruise data well. There is only about 7cm difference in the means and 20cm between the medians. The model also reflects the bimodal distribution of ice thickness along the SCICEX 1999 track well.

The model gives good estimates of ice thickness most of the time. Figures 10 through 19 show PDFs for ten other cruises whose ice thickness distributions were closely estimated by the model. The weighted model mean ice thickness was within 0.3m of the data mean ice thickness for 11 of the 19 U.S. submarine cruises for which data was available (Figure 20). The model also tended to represent the ice thickness distribution for these cruises well.
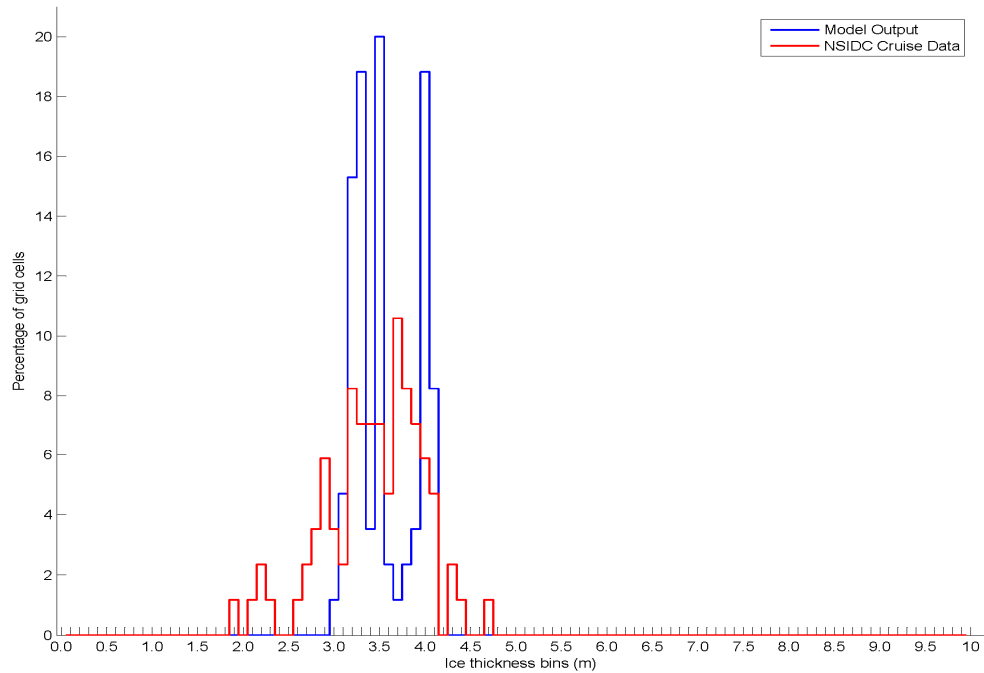
Figure 8.   1999 SCICEX cruise segment by segment average ice thickness and corresponding model monthly mean segment-average PDFs.

Figure 9.   1999 SCICEX cruise segment-weighted average ice thickness and corresponding model monthly mean weighted segment-average PDFs.

Figure 10. Middle third of April – first third of June 1986 cruise segment-weighted average ice thickness and corresponding model monthly mean weighted segment-average PDFs.

Figure 11. Last third of May 1988 cruise segment-weighted average ice thickness and corresponding model monthly mean weighted segment-average PDFs.

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Figure 12.   Last two-thirds of September 1989 cruise segment-
weighted average ice thickness and corresponding model
monthly mean weighted segment-average PDFs.
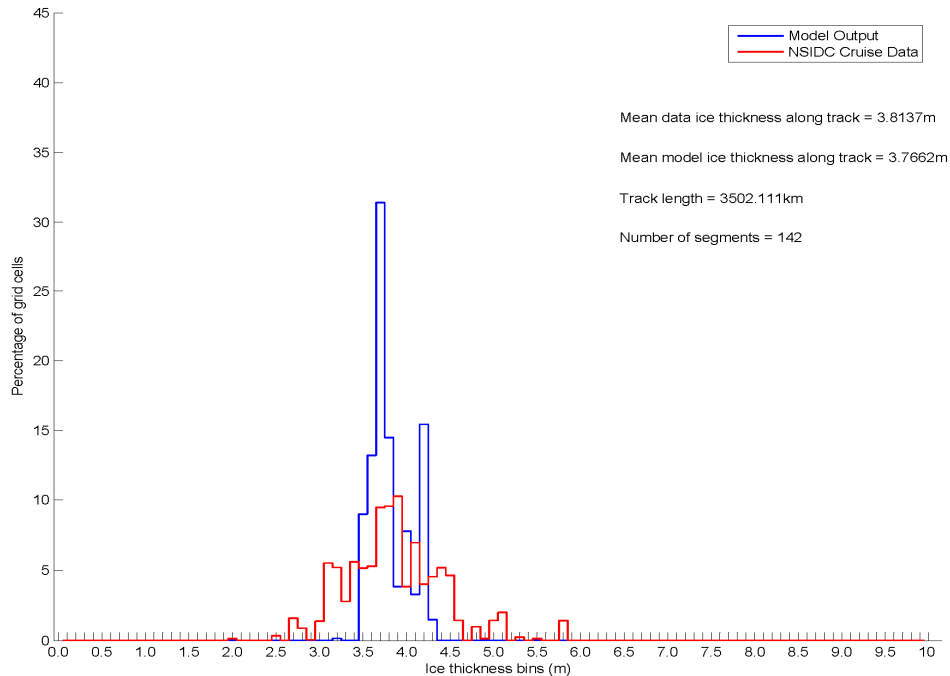
Figure 13.   Last third of March – middle third of May 1991
cruise segment-weighted average ice thickness and
corresponding model monthly mean weighted segment-
average PDFs.
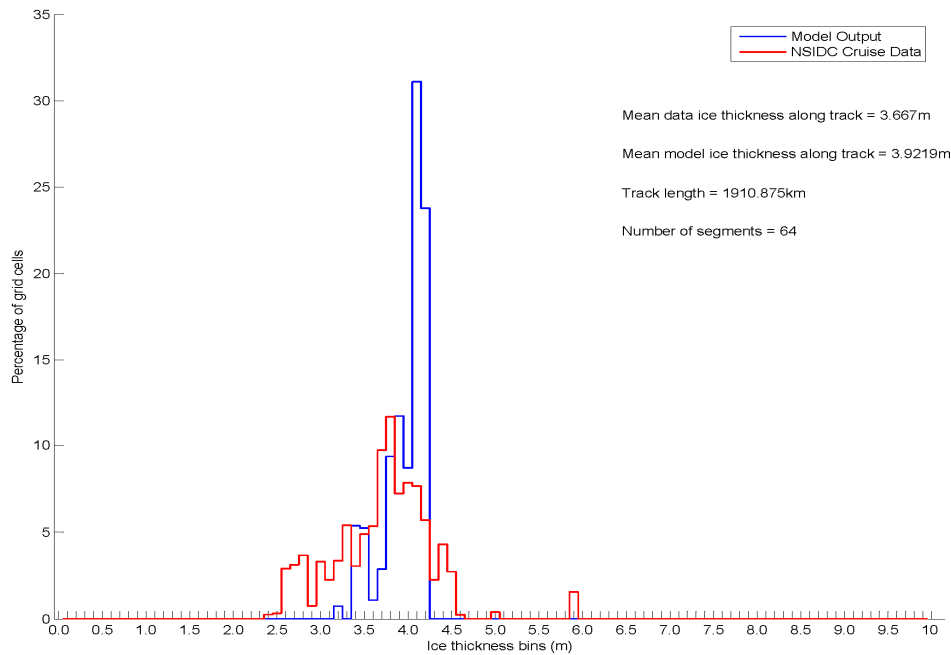
Figure 14.   Last Middle third of April 1992 cruise segment-
weighted average ice thickness and corresponding model
monthly mean weighted segment-average PDFs.
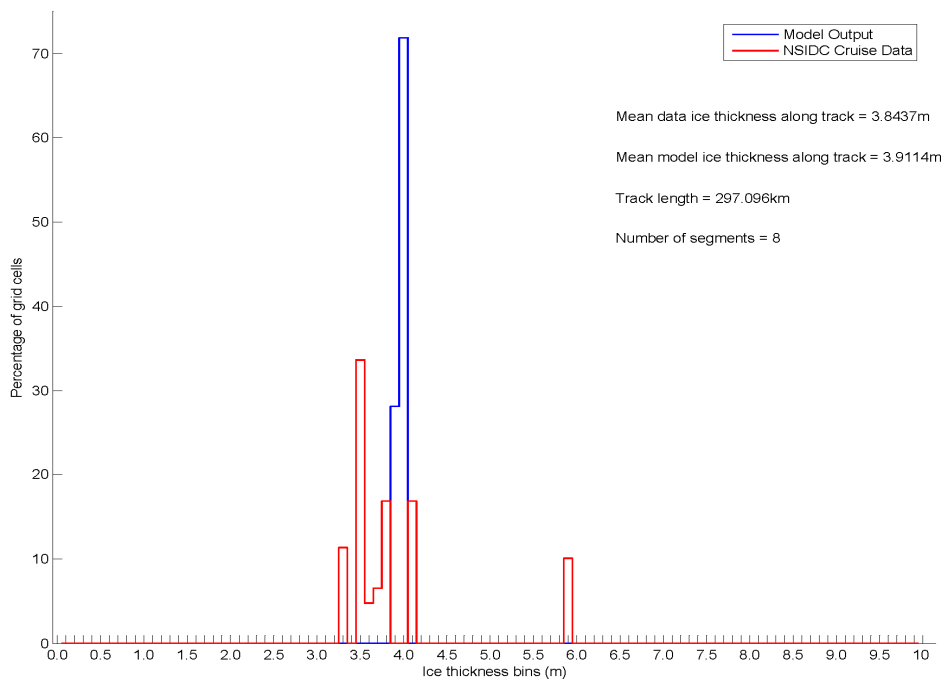
Figure 15.   Middle third of April 1992 (USS GRAYLING) cruise
segment-weighted average ice thickness and
corresponding model monthly mean weighted segment-
average PDFs.
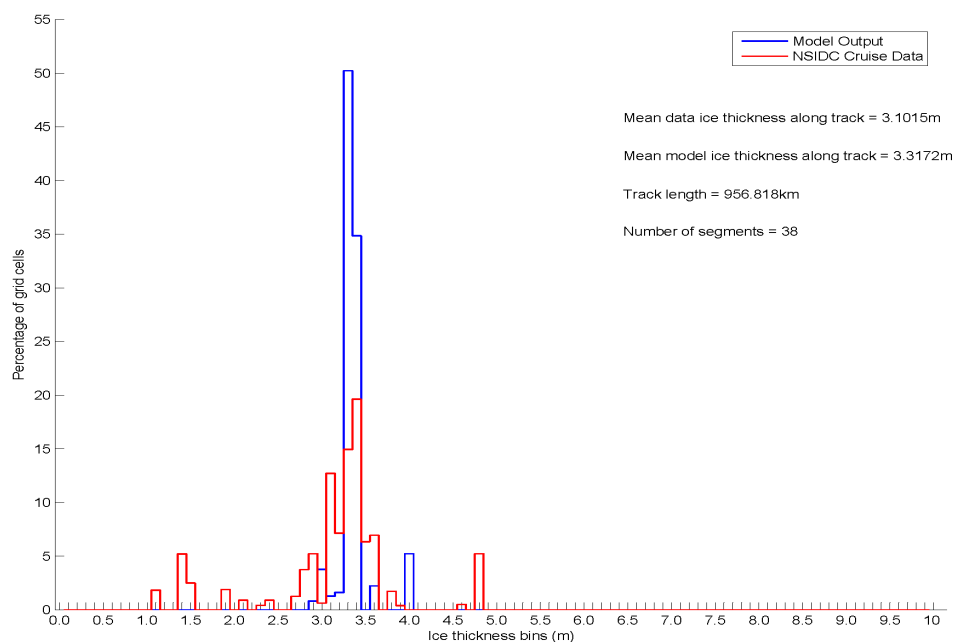
Figure 16.   Last third of August – first third of September
         1992 cruise segment-weighted average ice thickness and
            corresponding model monthly mean weighted segment-
                          average PDFs.
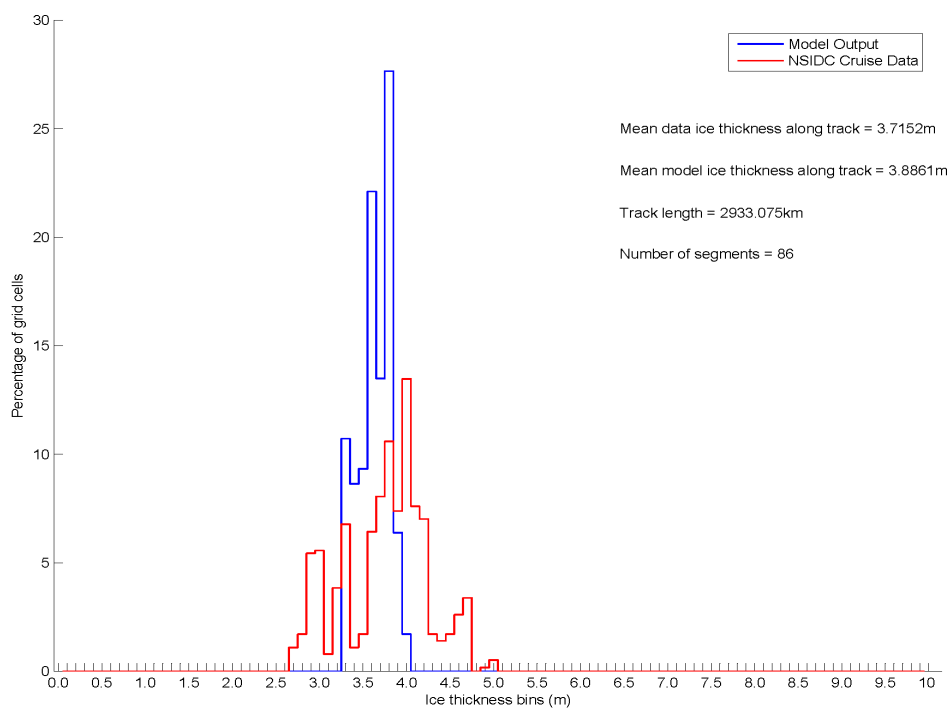
Figure 17.   Last two-thirds of April 1993 cruise segment-
        weighted average ice thickness and corresponding model
             monthly mean weighted segment-average PDFs.

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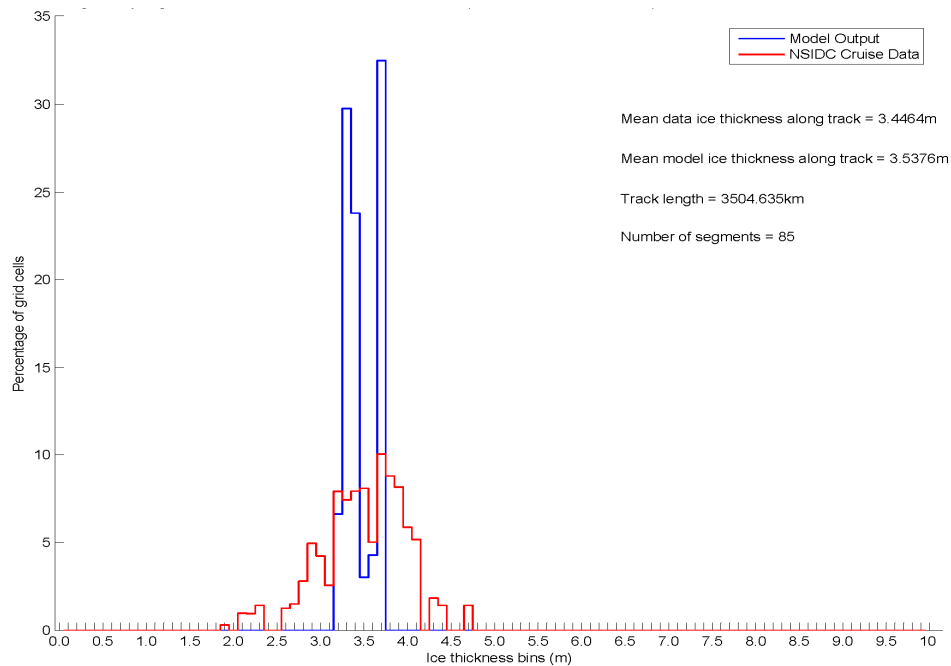
Figure 18.   First third of April 1994 cruise segment-weighted
average ice thickness and corresponding model monthly
mean weighted segment-average PDFs.
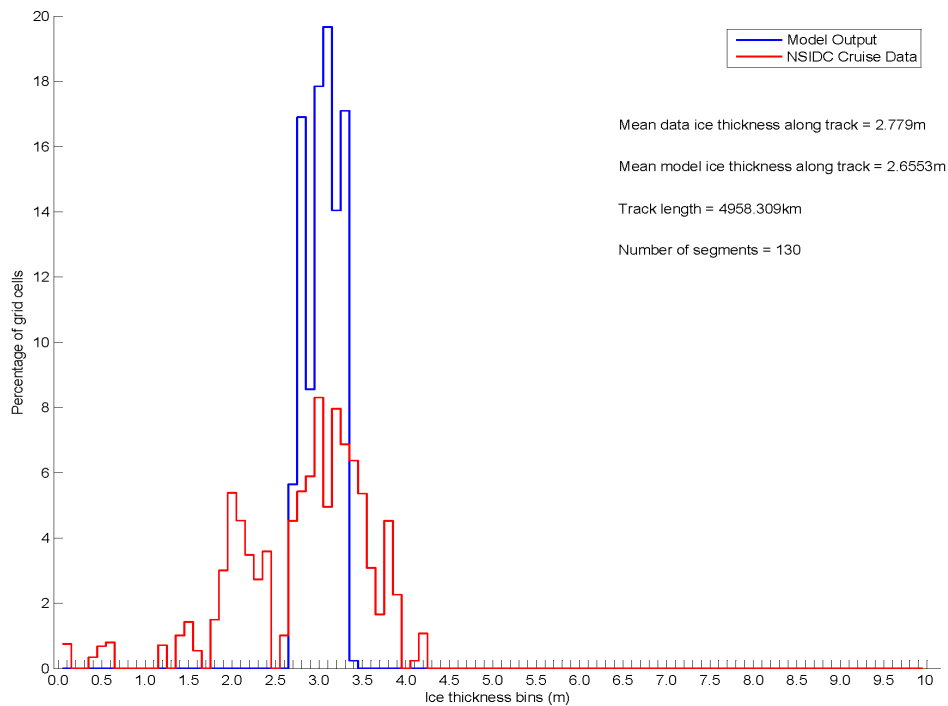
Figure 19.   02-16 August 1998 SCICEX cruise segment-weighted
average ice thickness and corresponding model monthly
mean weighted segment-average PDFs.

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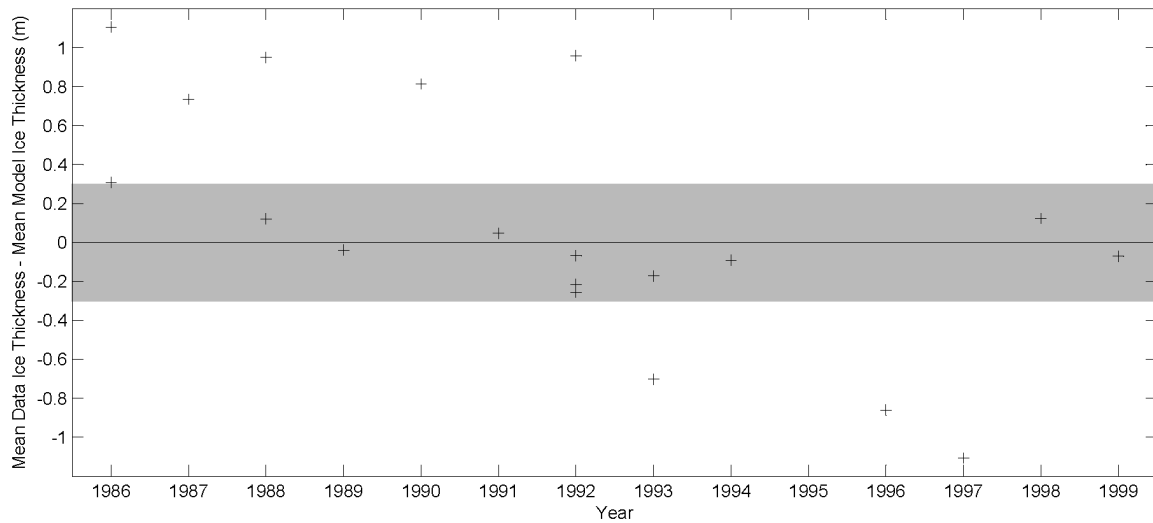
Figure 20. Plot of the differences between mean data thickness and mean model thickness for U.S. submarine cruises 1986-1999. The shaded band represents tracks for which the data and model mean thicknesses are within 0.3m of one another.

It can be seen from Figure 20 that while the majority of the cruises were well represented by the model (the mean data and model ice thicknesses are within 0.3m of one another for these cruises), it failed to accurately represent the ice thickness mean for the rest. In some instances the model overestimated ice thickness, such as the 1997 SCICEX cruise, 3 September through 2 October 1997 (Figure 21). In other cases, the model underestimated ice thickness, such as for the 1986 cruise that took place during the last two-thirds of April (Figure 22). The model also tended to poorly represent ice thickness distribution for these cruises.

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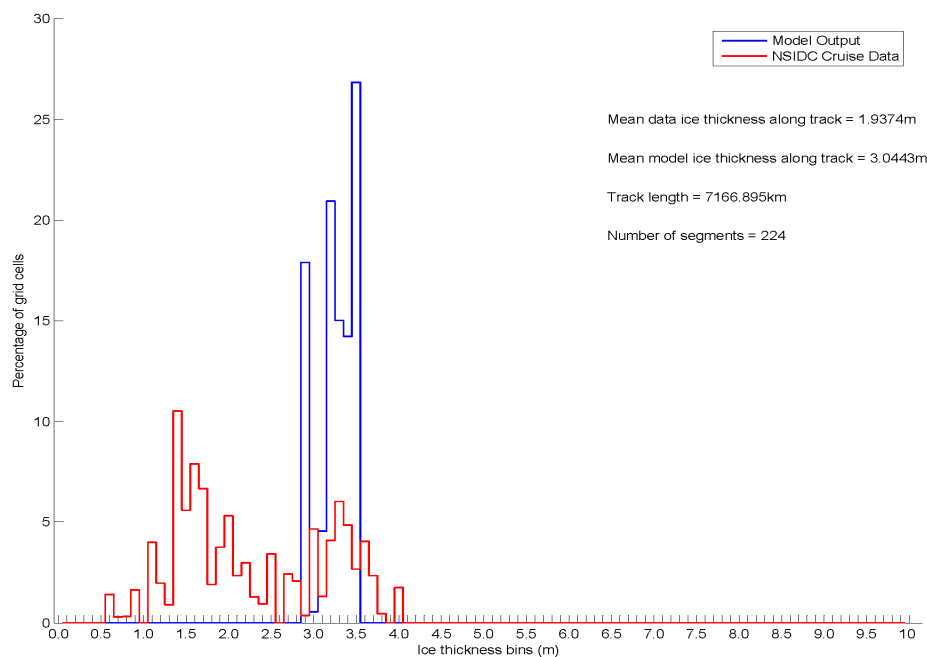
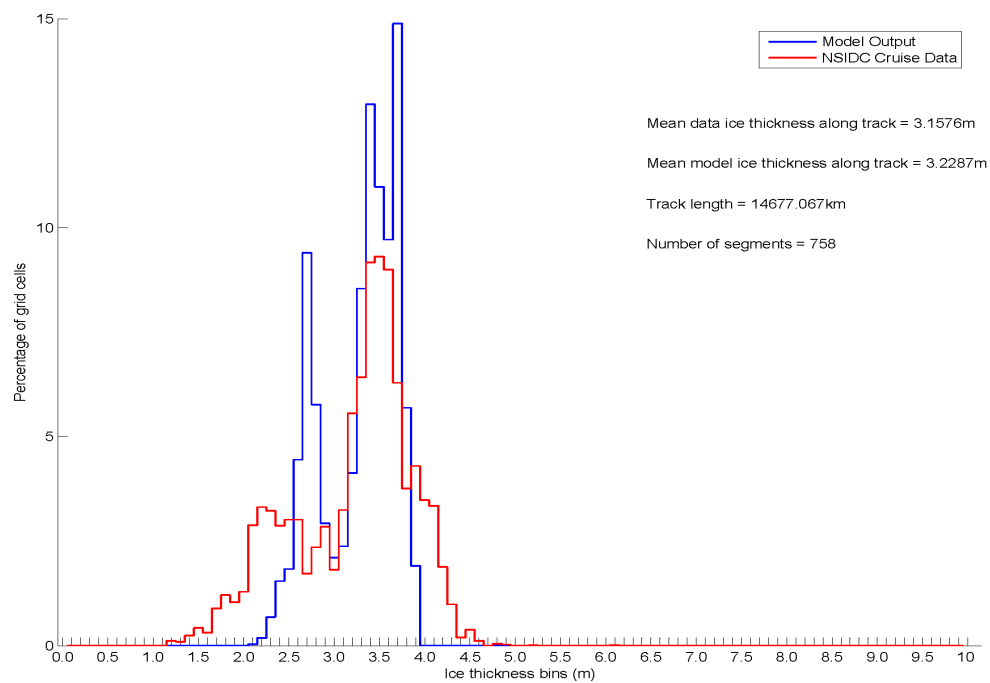Figure 21.   3 September through 2 October 1997 SCICEX cruise segment-weighted average ice thickness and corresponding model monthly mean weighted segment-average PDFs.
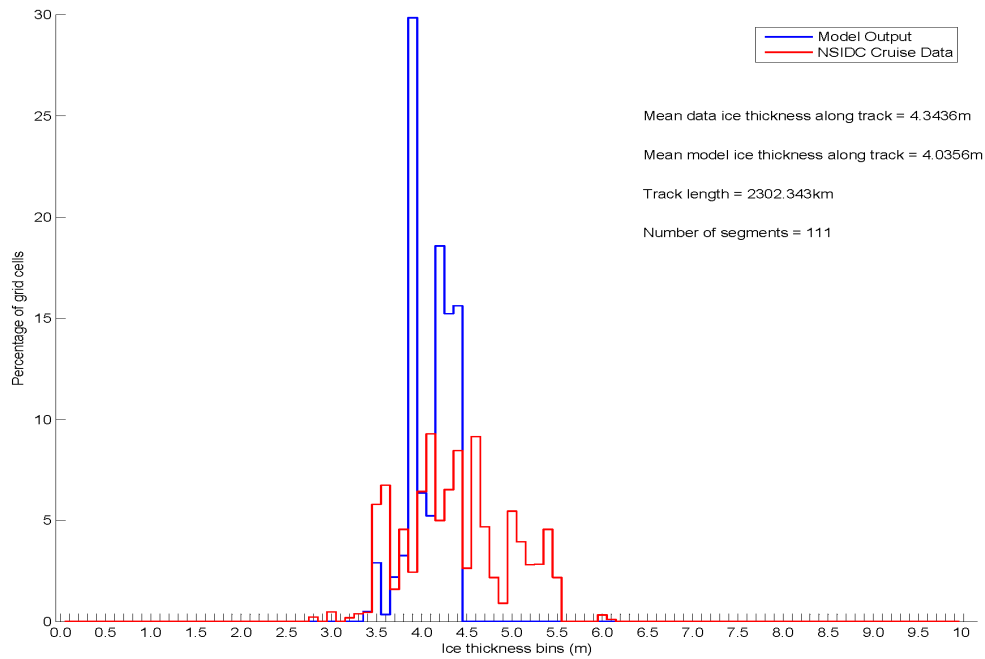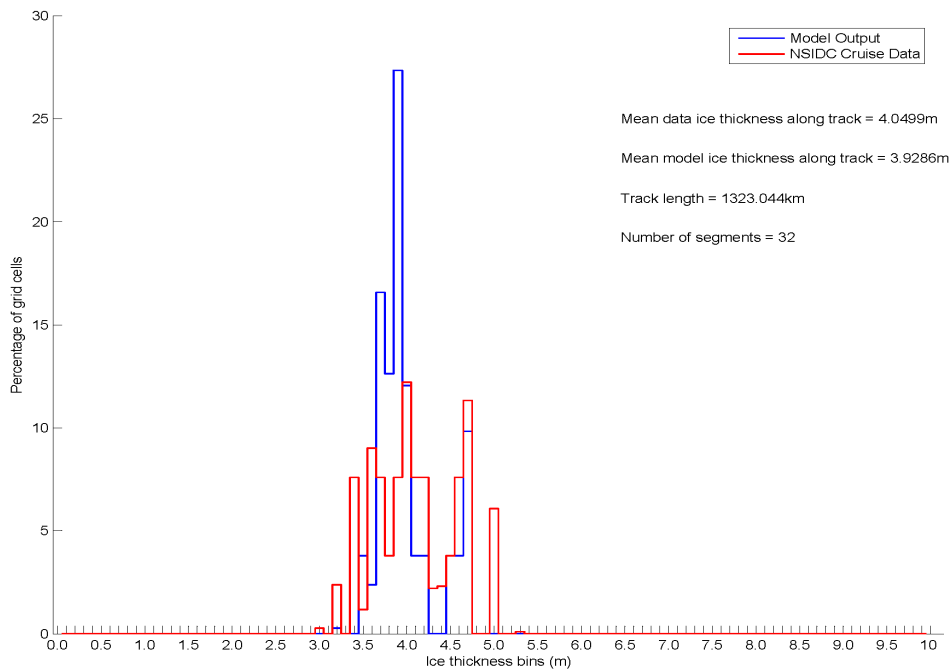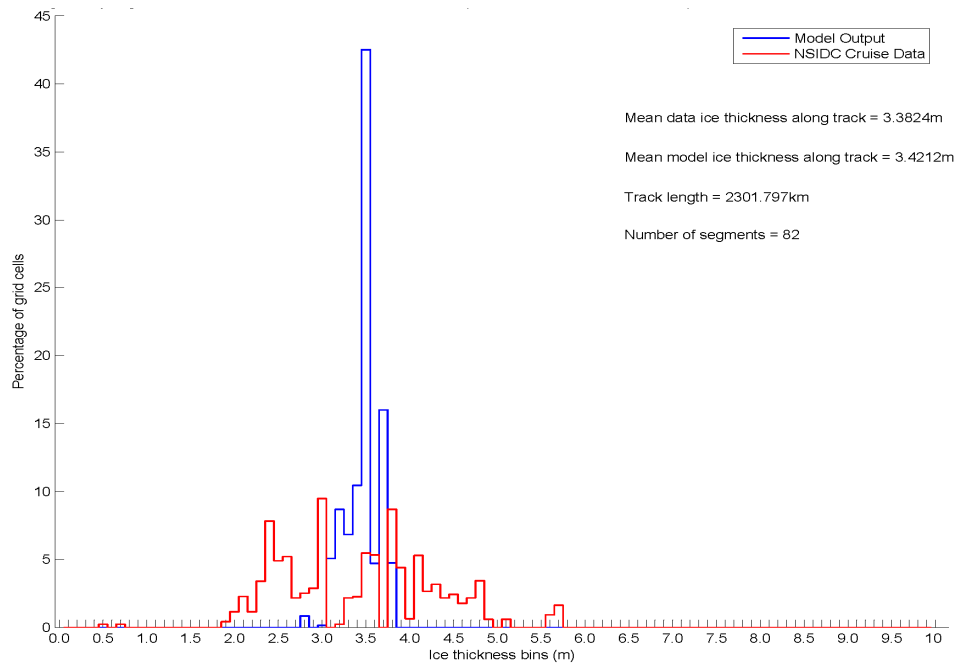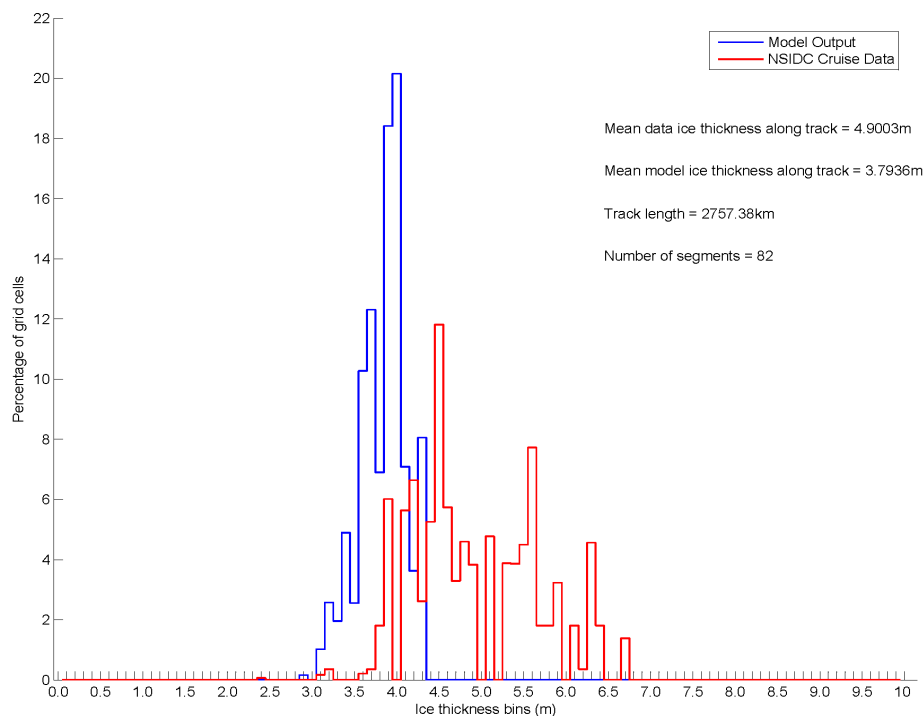

Figure 22.   Last two-thirds of April 1986 cruise segment-weighted average ice thickness and corresponding model monthly mean weighted segment-average PDFs.

It is difficult to draw any firm conclusions from the cruises where the model and data means differed widely - the outliers in Figure 20. In general, the cruises for which the model underestimated ice thickness were in the period 1986-1992 and the cruises for which the model overestimated ice thickness were 1993 and on. However, the number of these outliers is small, making them a suspect basis for a conclusion of model bias and/or a change in model bias in 1992. The cruise datasets are also not directly comparable to one another due to differences in location, track length (number of data points) and time of year.

B.   COMPARISON OF GREENICE 2003 DATA WITH MODEL OUTPUT

The GREENIce 2003 field campaign yielded ice thickness datasets for eight flights. These flights were conducted on different days and locations during the month of April 2003. Due to the relatively slow speed of R/V POLARSTERN and the limited range of the helicopter, all the surveys were conducted in a small area (Figure 3).

The datasets contained data points that had negative values for ice thickness or no value at all. These data points were removed before any further data processing was performed for this study.

As with the submarine ULS data, the HEM data is unsuited to direct comparison with model output due to the number of data points being much larger than the number of model cells. In the most extreme case, 4 April 2003, a single model cell encompasses the region covered by the data (Figure 23).
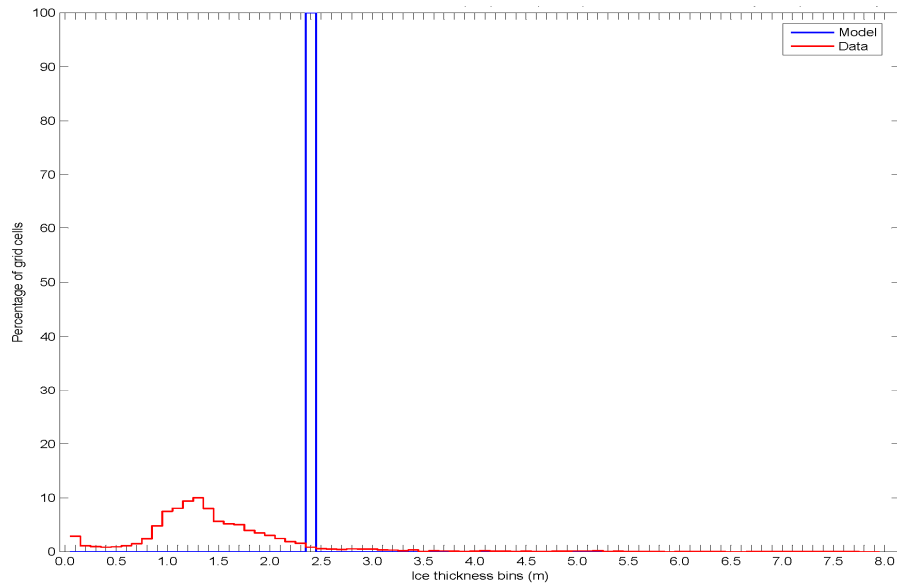
Figure 23.   4 April 2003 GREENIce HEM ice thickness and
corresponding model ice thickness PDFs.

Even combining several days' worth of data and using a
larger model area that surrounds the survey area does not
improve the picture much (Figure 24).
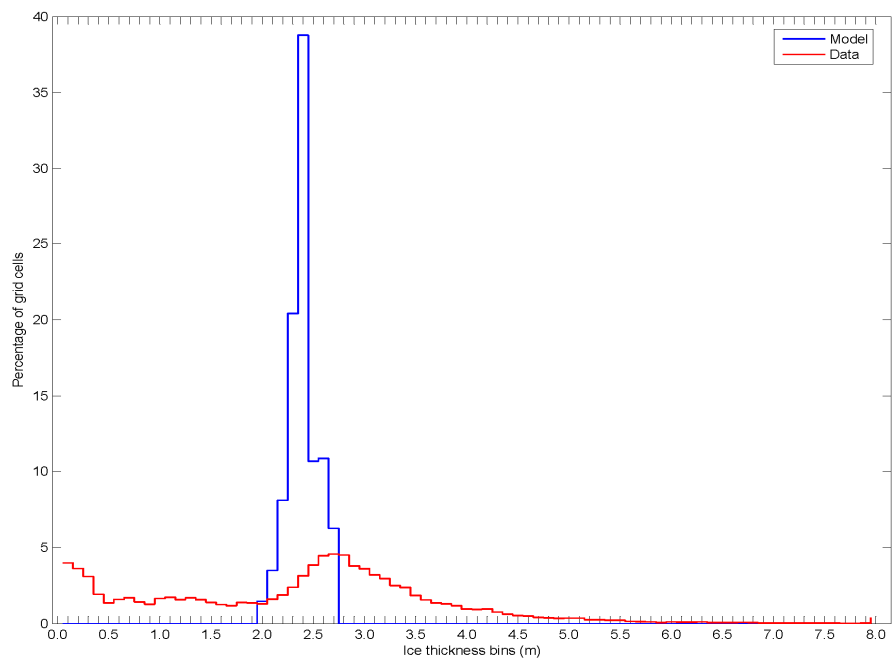
Figure 24.   4 through 19 April 2003 GREENIce HEM ice thickness
PDF and model ice thickness PDF for the model area
(199≤x≤830, 462≤y≤478).

A solution to the mismatch in spatial resolution between data and model is to compute the average ice thickness measured by HEM within each model cell and then compare the cell-averaged ice thickness PDF with the PDF of model thickness from the same cells (both PDFs weighted by the number of data points in each cell).

The aggregate picture is cleared up somewhat, though the model PDF does not show the distribution shown by the data (Figure 25). This is because the HEM flights took place in such a small area (Figure 3) that the model cells associated with them overlap to a large degree. This contrasts with the submarine cruise tracks, which do not cross over themselves - and thus overlap - often.
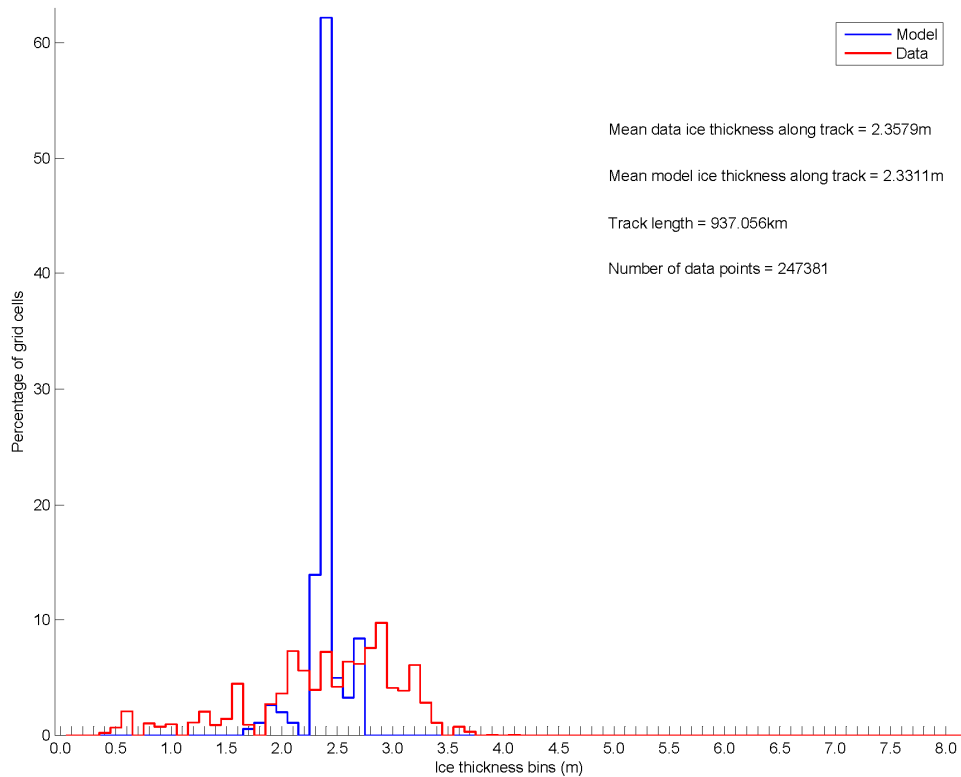
Figure 25. 1 through 19 April 2003 GREENIce HEM cell-averaged ice thickness and corresponding model ice thickness PDFs and summary statistics.

While spatial resolution severely limits the model's ability to represent ice thickness distribution in GREENIce's survey area, the weighted average means are less than 3cm apart. While the model weighted mean ice thickness was close (within 30cm) to the HEM mean in only five of eight flights, it is interesting to note that these were the five longest flights (all over 100km), which have the most data points.

C.   COMPARISON OF 2003 ICESAT DATA WITH MODEL OUTPUT

Since this study focuses on the Arctic, all data south of 75° North between 120° West and 120° East and south of 65° North everywhere else were ignored (Figure 26). The ICESat altimetry data used in this study spans two periods in 2003: 20 Feburary through 29 March and 4 October through 18 November. Figure 27 shows the tracks of the satellite during each of those months.
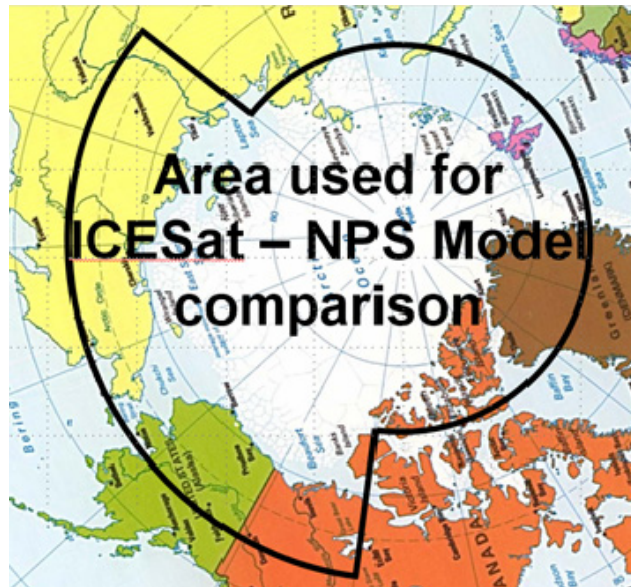
Figure 26.   Map rotated to match Figure 5, showing the area for which ICESat data and model output was compared. [After http://www.lib.utexas.edu/maps/islands_oceans_ poles/arctic_region_pol_95.jpg, Feb 2006]
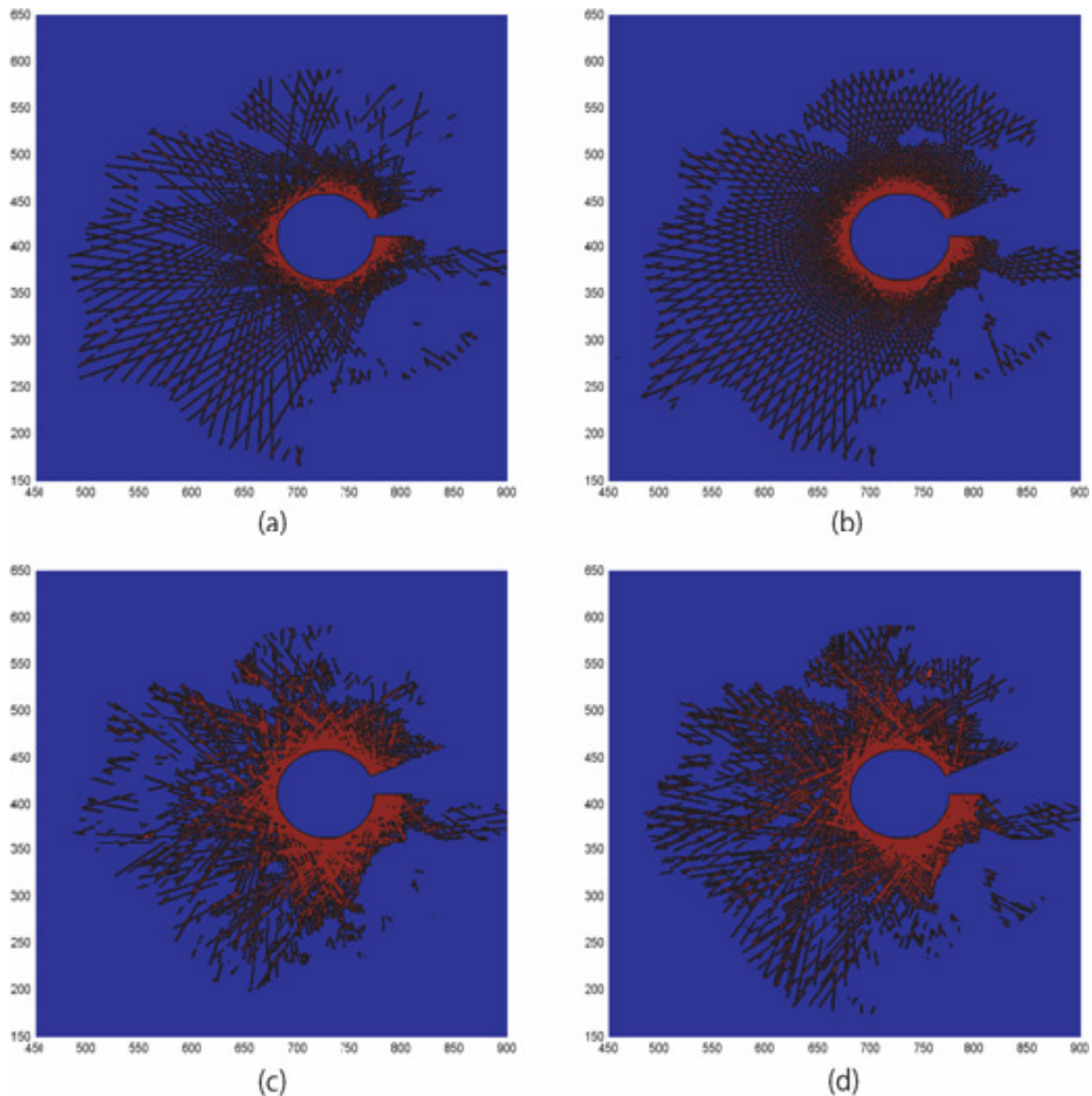
Figure 27.   The distribution of ICESat data used in this study.
The scales are the model grid X and Y coordinates.
Each red dot is a cell for which there was data within
the area of interest (Figure 26). The plots show the
spatial distribution of data for (a) 20-28 February
2003, (b) 1-29 March 2003, (c) 4-31 October 2003, and
(d) 1-18 November 2003.

Again, this data was averaged in order to match the
spatial and temporal resolution of the model output so data
and model could be compared. The satellite ice thickness
data occurring in each of the four months were averaged by

grid cell. The PDF of ice thickness by ICESat for each of
the four months was computed from these averages and
plotted along with the PDF of model ice thickness for the
same month and set of grid cells. The mean ice thickness
of the data and model output (again for the same cells) for
the four months in question were also computed. The PDFs
and means can be seen in Figures 28-31.
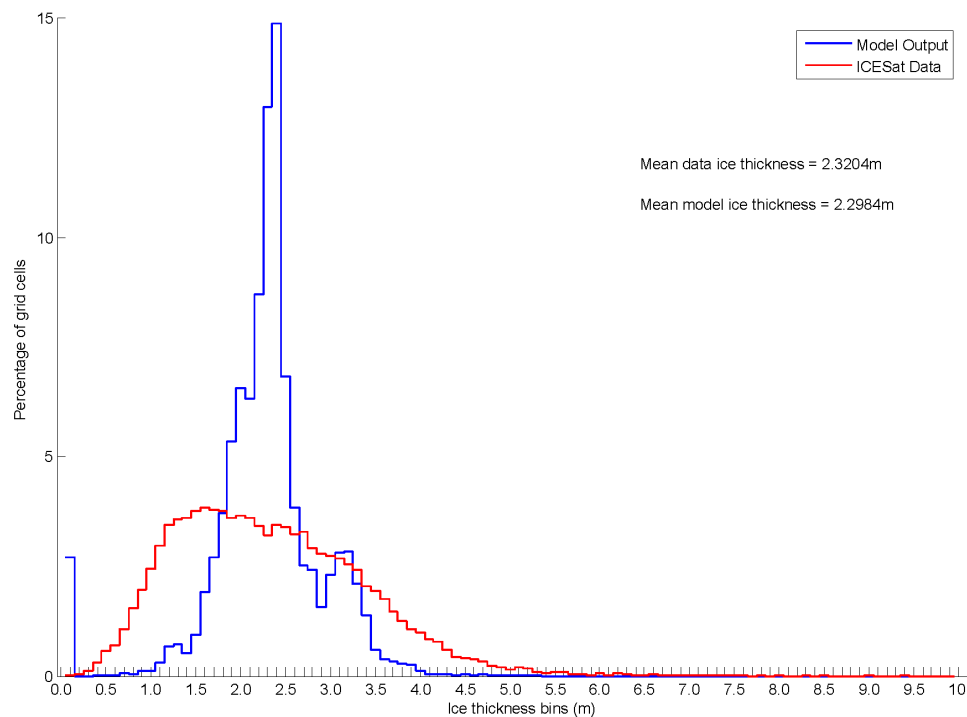
Figure 28. 20-28 February 2003 ice thickness as measured by
         ICESat and corresponding model ice thickness PDFs and
                      mean ice thickness.
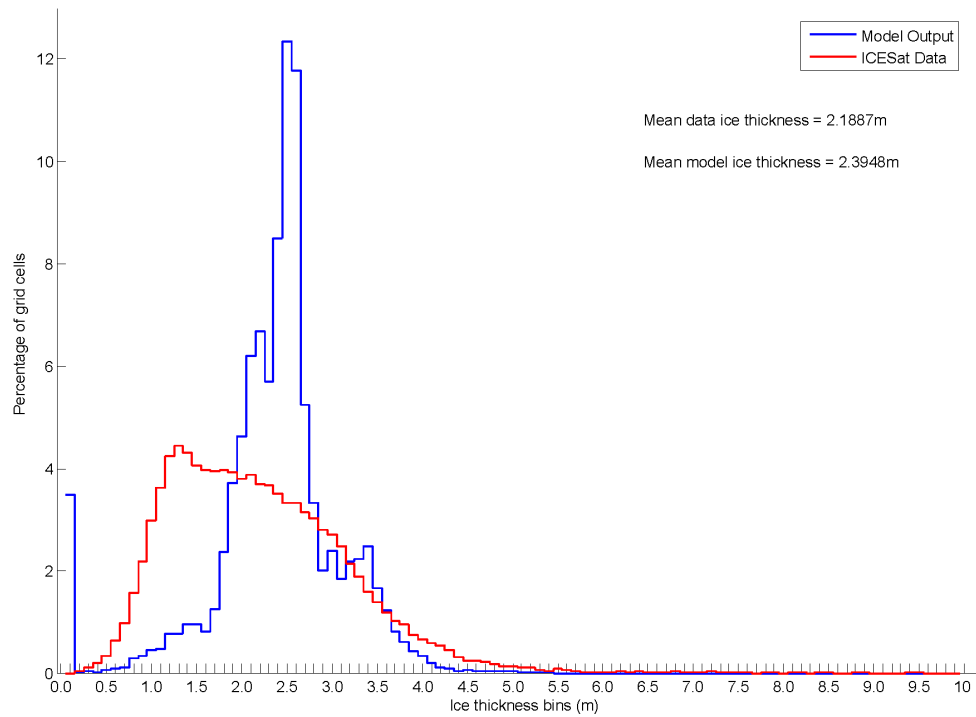
Figure 29. 1-29 March 2003 ice thickness as measured by ICESat and corresponding model ice thickness PDFs and mean ice thickness.
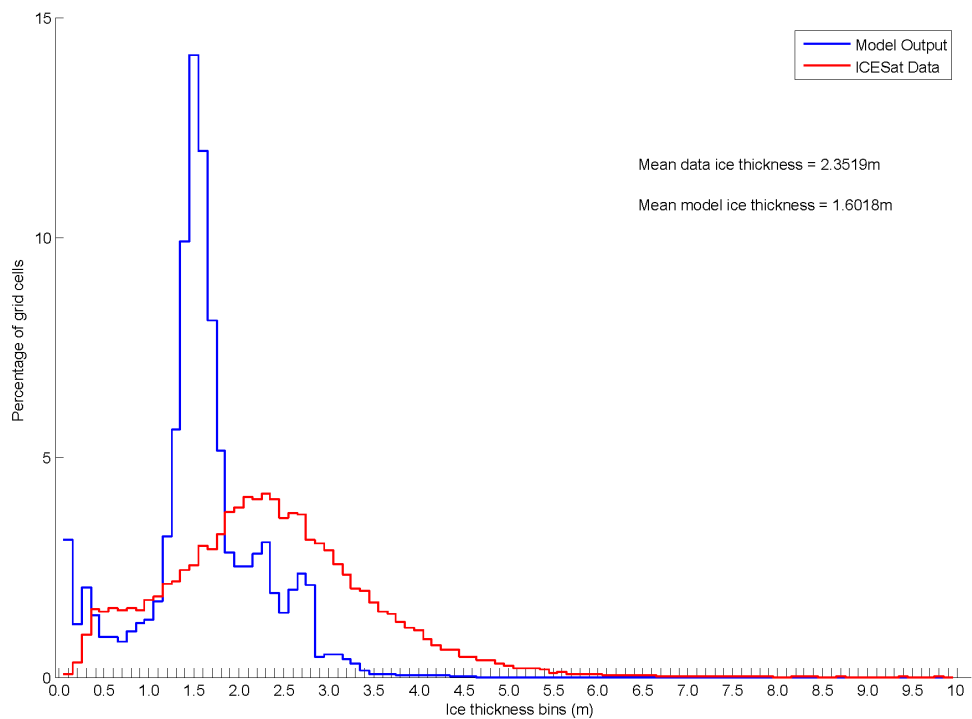
Figure 30. 4-31 October 2003 ice thickness as measured by ICESat and corresponding model ice thickness PDFs and mean ice thickness.
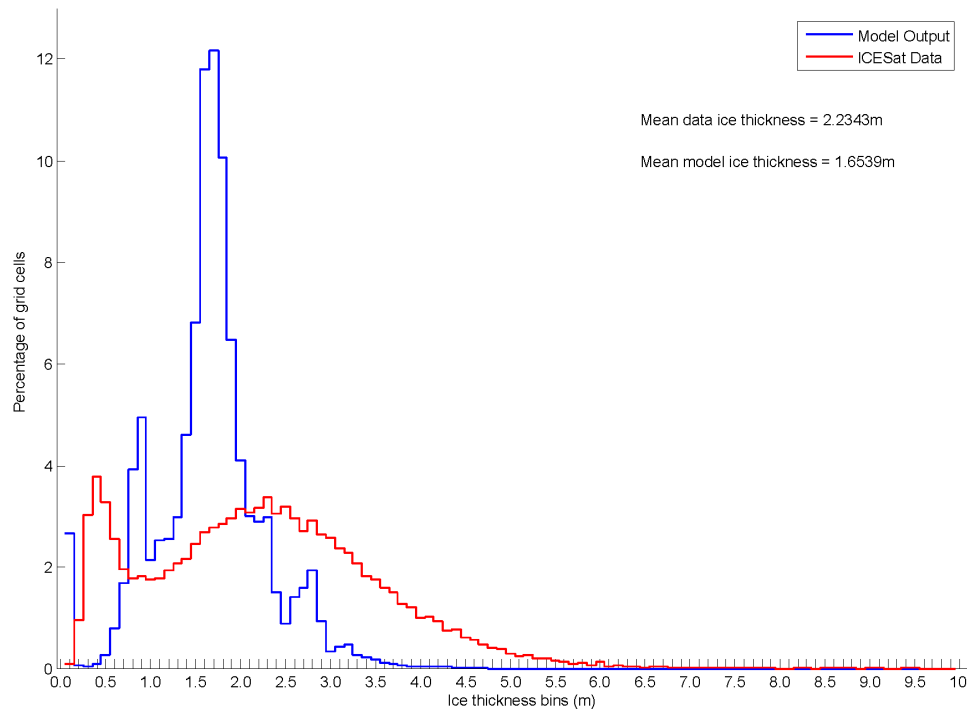
Figure 31. 1-18 November 2003 ice thickness as measured by
ICESat and corresponding model ice thickness PDFs and
mean ice thickness.

As can be seen, the model agrees quite well with the
data mean thickness for February and March. However, the
model did not match the ICESat ice thickness distribution;
the model displays a bimodal distribution for those two
months that is not reflected in the satellite data.
Moreover, the model median thickness for February 2003 is
2.4m, which is 0.8m greater than the data mean thickness.
For March, the model median thickness is 2.5m, which is
1.2m greater than the data mean thickness. Conversely, the
model underestimates both mean and median on October and
November. The model does, however, do a better job showing
the shape of ice thickness distribution in October and
November.

The mean ice thickness values for October and November
(after the melt season) are slightly higher than those for

February and March (the coldest part of winter). This is
consistent with the findings of Bourke and Garrett (1987),
that mean ice thickness is higher in summer than in winter
(see Chapter 1).

IV. RELIABILITY OF METHODS AND SOURCES OF ERROR

A. SUBMARINE UPWARD-LOOKING SONAR

The ice thickness data derived from submarine ice drafts is probably the most reliable of the three methods of collecting ice thickness data used in this study. It has two main advantages. The first is that it uses relatively well-proven technology, namely depth gauges and ULS. The second advantage is that submarine-measured ice draft measurements represent a large fraction of total ice thickness (80-95%) (Bourke and Garret, 1987), meaning that a relatively small fraction needs to be extrapolated to determine total ice thickness. More comprehensive discussions of the pros and cons and accuracy of submarine-derived ice thickness data can be found in Bourke and Garret (1987), Bourke and McLaren (1992) and McLaren et al. (1992).

While the extra data points at certain thicknesses that show up in Figure 2 appear to be some sort of data processing error, it is assumed that the averaging process used to compare submarine data with model output minimized this source of error. Certainly, the spikes seen in Figure 2 are nowhere in evidence in Figures 9 through 19.

The other main source of error is the use of a constant factor to convert ice draft measurements to ice thickness. Though this simple method does not take into account spatial variations in water density, ice density and snow load, it is assumed that the error is small since, as stated above, a relatively small fraction of ice thickness needs to be extrapolated from daft measurements.

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B.   HELICOPTER-BORNE ELECTROMAGNETIC SENSOR

As stated in Chapter II, the main advantage of the HEM method is that it is able to simultaneously measure the distance from the sensor of the top and bottom surfaces of the ice, eliminating the need for the extrapolation used in the other two methods. The types of instruments used are not new; EM sensors placed directly in contact with the ice had been used before to good effect (Haas, GRL, 2004), and aircraft-mounted laser altimeters have been used before to measure ice freeboard (Bourke and Garrett, 1987). However, the combination of laser altimeter and airborne EM sensor as used by the GreenICE 2003 expedition was new and thus subject to uncertainties associated with using a new system (Haas, AWI, 2004).

Obviously erroneous data, such as gaps and negative thickness data points were removed prior to processing for this study. It should be noted that the large number of negative ice thickness data points brings up concerns about the accuracy and/or bias of the measurements. Haas (AWI, 2004) discusses the uncertainties inherent in the HEM methods in detail. For this study, it assumed that all non-negative HEM ice thickness measurements are correct.

C.   ICESAT LASER ALTIMETRY

The main source of uncertainty in the ICESat data stems from the fact that the laser measures freeboard, which is a relatively small fraction (10-15%) of total ice thickness. As stated in Chapter II, the advertised accuracy of ICESat's altimeter is 10cm. Any errors are magnified by the extrapolation of ice thickness. Moreover,

this extrapolation is very sensitive to variations in water and ice density and snow load.

The ICESat datasets provided for this study include extrapolated ice thicknesses. While constant ice and sea water densities are assumed, snow load from a model is incorporated in the calculation of ice thickness. The snow model (both snow thickness and snow density) is based on a study by Warren et al. (1999) that assimilated and interpolated Arctic snow data between 1954 and 1991. The snow thickness must be added to the satellite's altitude as the laser reflects off the surface of the snow, unlike radar, which penetrates snow cover. The weight of the snow, calculated from both the thickness and the density of the snow cover, must also be taken into account as it makes the ice sink deeper into the water than it would otherwise. While certainly better than nothing, the snow model introduces an extra degree of uncertainty into the final ice thickness measurements since it is a model and because the study on which it is based, like most Arctic research, was hampered by sparse data.

For the purposes of this study, it must be assumed that the ICESat ice thickness numbers are correct within the specified accuracy, apart from some corrupt data that was removed prior to processing. It is hoped that the spatial and temporal averaging done for the comparison with the NPS model has additionally averaged out some errors.

D.   TEMPORAL RESOLUTION

A potential source of error common to the three comparisons performed in this study arises from the mismatch in temporal resolution. Apart from non-SCICEX submarine data, the time of the observations included the datasets used in this study is known at least to the day, a marked contrast to the monthly average model output available for analysis. Even the data from declassified submarine cruises is given to the nearest third of a month, better temporal resolution than the model output.

It is assumed that much of the error is averaged out when comparing datasets that span most or all of a month. However, some datasets span relatively short periods of time, such as the February 2003 ICESat data (eight days), the April 1994 submarine cruise (one third or less of a month), and each of flight of the GreenICE 2003 field campaign (one day each). In these cases, there is likely to be a substantial mismatch introduced into the comparison since ice thickness is constantly changing over time due to various factors such as freezing, thawing, ridging and ablation. It is also likely that a dataset consisting of observations taken only at the beginning or end of the month will show a bias when compared to a model monthly average, especially if it is a month when ice is rapidly freezing or melting.

V.   DISCUSSION

A.   MODEL SKILL

As seen in Chapter III, the NPS model, while not
perfect, represents ice thickness well most of the time in
the areas and periods for which ice thickness data is
available. This provides a solid basis for the assumption
that the model does an equally good job representing ice
thickness everywhere else.

It is clear that the analysis presented here is
limited by the spatial resolution of the model used. The
approximately 9km x 9km grid cells of the model
necessitated the averaging of observed data discussed in
Chapter III. This averaging resulted in the loss of small
spatial scale variations in ice thickness (especially with
the HEM data) and effectively eliminated much of the data
on very thin and very thick ice. The next generation of
NPS Arctic model will solve these problems to some extent
as its planned spatial resolution will be 1/48-degree, or
approximately 2.3km. Its output will also incorporate ice
thickness distribution for each cell (Maslowski, 2006),
further reducing the amount of data "averaged out" in
future comparisons between model output and observed data.

B.   ARCTIC ICE PACK TRENDS

Analysis of the NPS model output by Maslowski (2006)
indicates that ice thickness is decreasing at a far greater
rate than that of ice extent. Figure 32 shows SSM/I
(Special Sensor Microwave/Imager) satellite radar-derived
ice extent and model-derived ice thickness for the Arctic

in the summers of 1987 and 2002 (excluding areas with ice
concentration less than 15%).
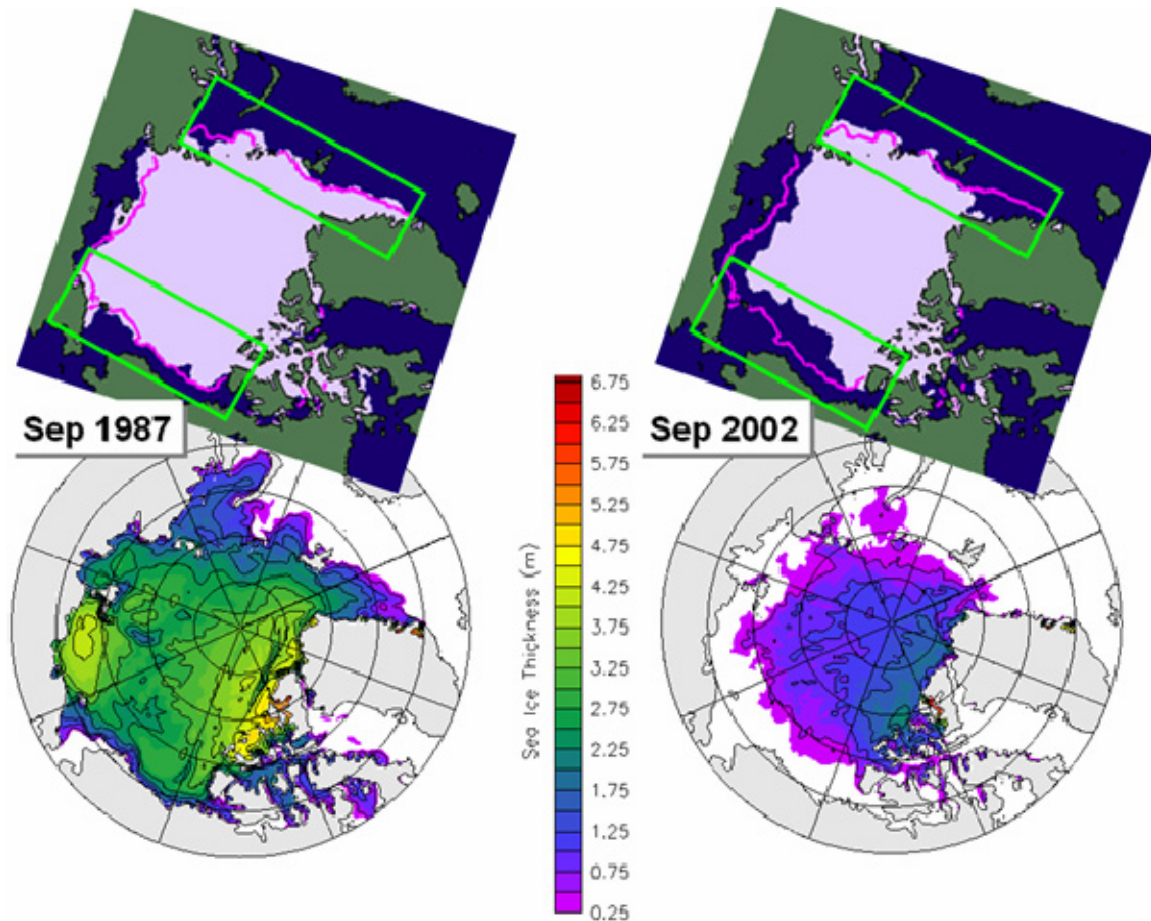
Figure 32.   Summer 1987 and 2002 Arctic ice extent and
distribution. The upper plots show SSM/I ice extent,
the lower ones NPS model output ice thickness
distribution. Areas with ice concentrations less than
15% are excluded. The pink line in the upper plots
represents mean ice extent for this time of year.
[After Maslowski 2006]

The reduction in ice extent between September 1987 and
September 2002 shown in Figure 32 is 15-18%. The reduction
in ice thickness for the same period is approximately 35%,
meaning that ice thickness decreased at about twice the
rate of ice extent. A look at plots of ice area and ice
thickness over time (Figures 33 and 34) indicates that

these dramatic reductions took place entirely in the last five years of this period: 1997-2002.

Combining ice area with ice thickness indicates an equally dramatic decrease in total ice volume (Figure 35). The reduction in ice volume, shown in Figure 35, amounts to approximately 33% between 1997 and 2002. At that time, September 2002 was the record low Arctic ice extent during the era of satellite observations (Francis et al., 2005). September 2003 and 2004, though slightly greater than 2002, were also extreme minima for ice area/extent (Stroeve et al., 2005).
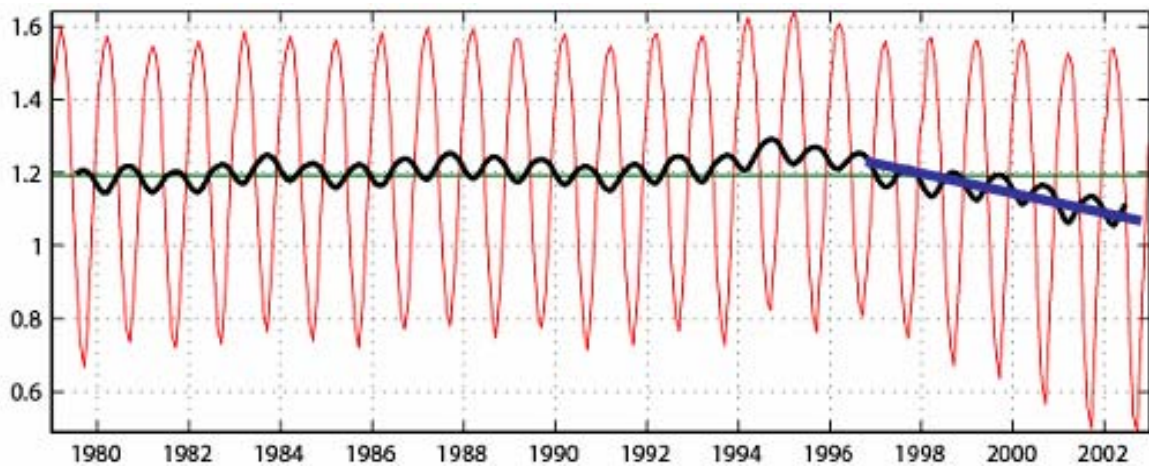
Figure 33. Arctic ice area over time from the NPS model. The plot shows ice area in km^2 x 10^7 versus time in red. The overall mean for the period shown is in green. The 13-month running mean is in black. The blue line shows the decreasing trend in ice area beginning in 1997. Areas with ice concentration less than 15% were excluded from the calculations. [After Maslowski 2006]
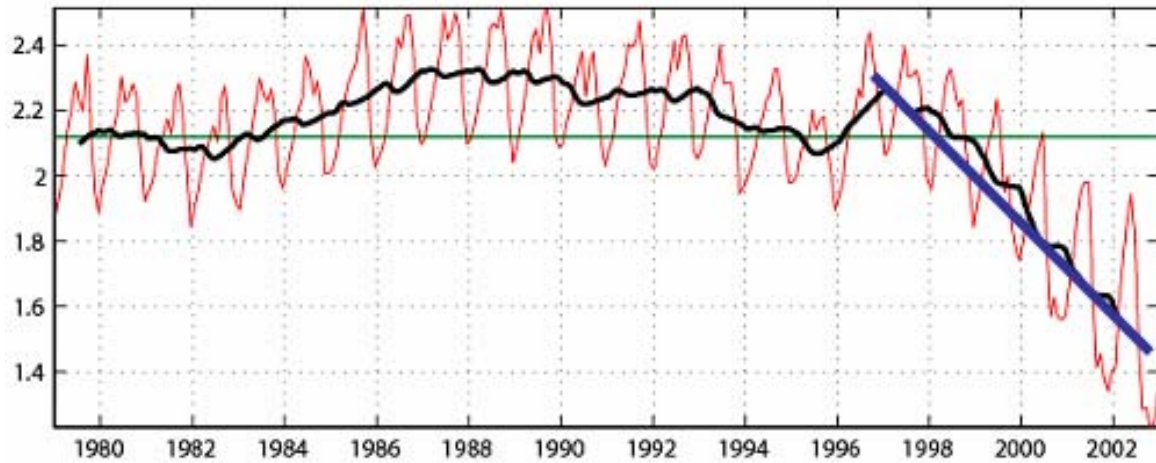
Figure 34. Arctic ice thickness over time from the NPS model.
This plot shows ice thickness in meters versus time in
red. The overall mean for the period shown is in
green. The 13-month running mean is in black. The
blue line shows the strong decreasing trend in ice
thickness beginning in 1997. Areas with ice
concentration less than 15% were excluded from the
calculations. [After Maslowski 2006]
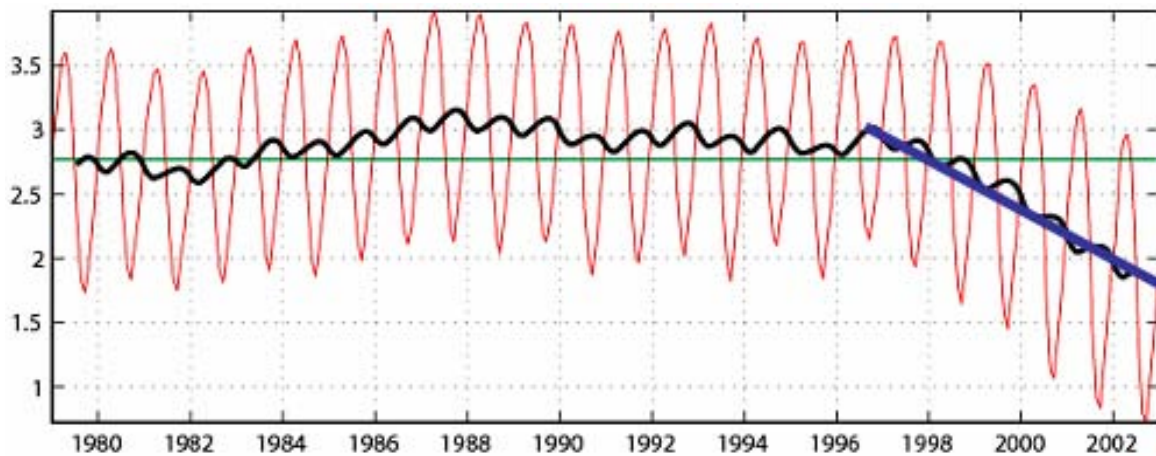
Figure 35. Arctic ice volume over time from the NPS model.
Ice area in km^3 x 10^4 versus time is in red. The
overall mean for the period shown is in green, the 13-
month running mean in black. The blue line shows the
strong decreasing trend in both ice area and thickness
beginning in 1997. Areas with ice concentration less
than 15% were excluded from the calculations. [After
Maslowski 2006]

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Lest it be thought that 2003 and 2004 were the
beginning of a recovery in Arctic sea ice extent, the NSIDC
(2005) has reported that September 2005 set a new record
minimum for ice extent.   The NSIDC also reports that
between 1978 and 2005, the trend for September sea ice
extent a decline of 8% per decade (Figure 36).
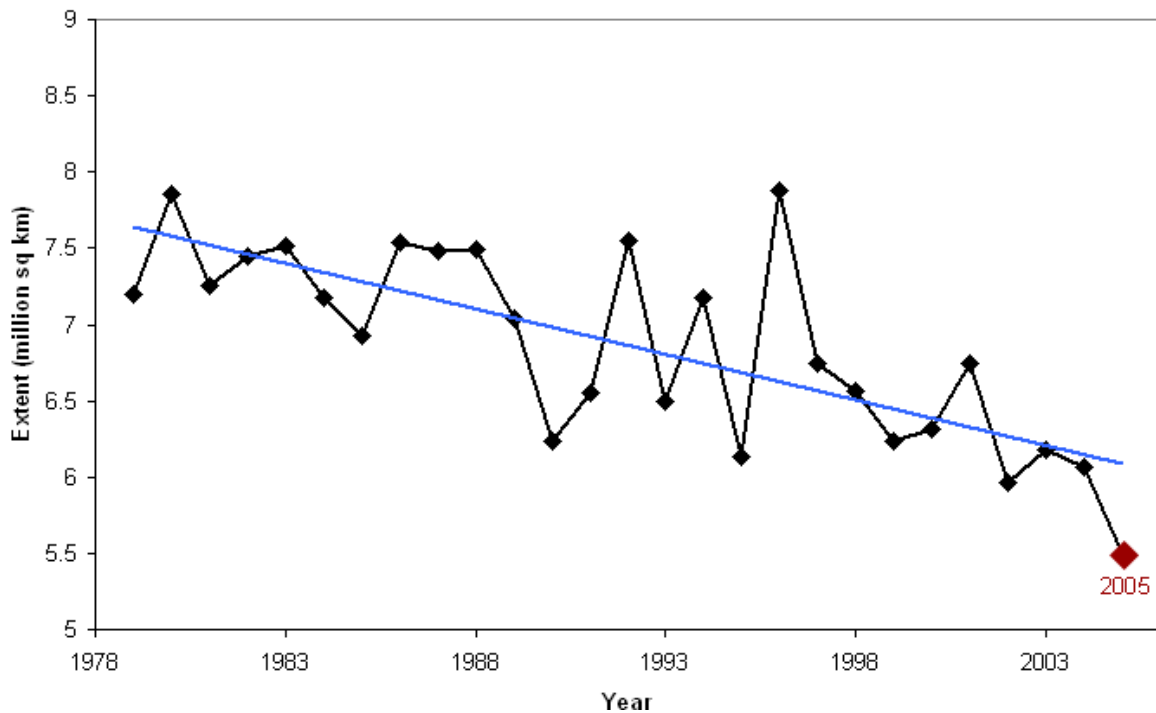
Figure 36.   The decline in sea ice extent from 1978-2005. The
        September trend from 1979 to 2005, showing a decline
         of more than 8 percent per decade, is shown with a
         straight blue line.   The value for 2005 was based on
          data through September 25; after this date, it is
          assumed that ice growth rates are typical for this
         time of year. Areas with ice concentration less than
        15% were excluded from the calculations. The area not
        imaged by the sensor at the North Pole was assumed to
              be entirely ice-covered. [From NSIDC, 2005]

        According to research at the NSIDC (2005), the
decreasing trend in ice coincides with a trend toward
higher surface air temperatures throughout the Arctic

region and earlier onset of the melt season. This research suggests that ice-albedo feedback (described briefly in Chapter I) could accelerate the decline in sea ice.

These dramatic trends in the Arctic beg the question of whether they can be halted or reversed. Since the ice-albedo feedback mechanism is one of positive feedback, it would take a change in ice-albedo interaction and/or a different mechanism to arrest the decline in sea ice we have been seeing. Overpeck et al. (2005) discuss several possible "brakes" on the system, but conclude that none of them is definitely going to stop the trends in Arctic warming and decreasing sea ice. They do note, however, that the crossing of "thresholds" could produce unexpected changes, underscoring the need for a system-wide understanding of the Arctic.

VI. CONCLUSION

Assuming we continue to have extremely low ice extents, and that the decreasing ice thickness trend continues, the Arctic could be ice-free in summertime within a decade (Maslowski, 2006). While this conclusion relies on a somewhat extreme interpretation of the available data, it is only extreme in terms of the rapidity of the predicted decrease in Arctic sea ice. A number of studies predict drastic ice reductions. For example, the U.S. Arctic Research commission's report on Arctic warming (Brass, 2002) concludes that a "conservative estimate" would be an ice volume reduction of 40% in the next half century. Overpeck et al. (2005) feel that entirely ice-free summers are a real possibility within a century. Whether it takes a decade or a century, the validation of the NPS model and the marked decreasing trend in Arctic sea ice indicated by the model provide strong evidence that the Arctic will soon be ice-free in summertime.

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VII.   RECOMMENDATIONS FOR FUTURE RESEARCH

A.   IMPROVED SNOW LOAD DATA

While historical snow load data will continue to be
based on models due to the sparseness of data, snow load
for 2003 onward could in principle be calculated for the
entire Arctic using satellite data. Since the ERS radar
altimeter penetrates snow cover and ICESat's laser
altimeter does not, the former detects the ice-snow
interface while the latter detects the snow-air interface.
It should therefore be possible to calculate snow thickness
for the entire Arctic (excluding the gap in satellite
coverage at northernmost latitudes) from these two
datasets. The resulting snow thickness dataset would
greatly improve the accuracy of extrapolations of ice
thickness derived from both ICESat altimetry and submarine
ULS and also would lead to better models.

B.   VALIDATION OF ICESAT ICE THICKNESS MEASUREMENTS

ICESat clearly has great potential for continuous
monitoring of the Arctic ice pack. However, nobody has yet
determined the true accuracy of ICESat laser altimeter-
derived ice thickness measurements. A comparison of ICESat
results with those obtained throughout the Arctic using
ERS, submarine ULS, and other methods would be most
helpful. This, in conjunction with the development of the
pan-Arctic snow thickness data recommended above, would
enable us to calibrate this system.

C. BETTER MODELS

We need to continue to develop improved models with better spatial resolution and more ice thickness categories (thickness resolution) that take advantage of new research on Arctic sea ice and advances in computing power. Models with predictive capability are needed for scientists and as an aid to government policy makers and other long-term planners.

D. IMPROVED AVAILABILITY OF ULS DATA

As mentioned in Chapter 1, submarines have been traveling under the Arctic ice pack since 1958. Not all of the ice draft data collected by the U. S. Navy and Royal Navy over the years is declassified. Even less of what is declassified has been processed into a format that can easily be used and made available to the public (the data offered by the NSIDC, almost all of which was used in this study, constitutes the entirety of such data). Further declassification and processing of ULS data is necessary to advance our understanding of the changes in Arctic sea ice in the last half-century. Since the Soviets began to operate submarines under the Arctic ice pack shortly after United States, it is likely the Russians also have quite a lot of data stored away. One can only hope the Russian government will also begin to declassify the data collected by Soviet and Russian submarines (as well as any other classified scientific research conducted in the Arctic over the years).

E.   IMPROVED MODEL TEMPORAL RESOLUTION

Due to data storage constraints, the NPS model's output consists of monthly averages. As discussed in Chapter IV, this temporal resolution is much poorer than that of the observed data used in this study. Future runs with this model and its descendants should have daily means saved for core sea ice parameters to improve our ability to compare model output with observed data.

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